CONCEPTUAL FRAMEWORK FOR INCORPORATING ACCESS FOR MAINTAINABILITY CONSIDERATIONS IN BIM COORDINATION

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CONCEPTUAL FRAMEWORK FOR INCORPORATING ACCESS FOR MAINTAINABILITY CONSIDERATIONS IN BIM COORDINATION

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To my parents and siblings, whose love and support have been invaluable.

In memory of Eleuterio Aparicio.

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SUMMARY

Facility managers have addressed access to perform maintainability tasks as one of the everyday struggles they face once the construction project is delivered. The development of Building Information Modeling (BIM) has proved the potential to foresee, identify, and remove the physical barriers for maintenance teams in order to allow better compliance of their tasks and to ensure that equipment is timely and adequately reviewed. Also, rule-based software might enhance the revision of the Americans with Disabilities Act (ADA) compliance checks, easing the decision-making process concerning end-user accessibility. Tools such as Solibri have rule templates for a few ADA checks. Nevertheless, there is not a framework that can provide complete operational constraints and foresees the avoidance of accessibility concerns during the design phase.

The objective of this study is to develop a proof of concept that addresses access for maintainability requirements during the coordination procedure, ensuring a welcoming and equitable environment for everybody. In order to introduce accessibility preconditions to an automated rule generator, the interpretation and reduction of the regulation need to be done first. Afterward, the decoded restrictions are introduced into a Dynamo script, which will make them visible on the clash detection tool during the coordination procedure. Later on, the proposed framework will be tested on a case study. The proposal might contribute to the reduction of the project's lifecycle costs by considering maintainability restrictions earlier in the design process.

Moreover, inputs related to disabled individuals' daily struggles might be further developed by fining tune the proof of concept. Therefore, those issues might be included

as a driver, following a human-centered design process. Furthermore, the incorporation of those constraints will contribute to the execution of a resilient building, capable of satisfying its occupants' displacement requirements.

CHAPTER 1. INTRODUCTION

This chapter introduces the problem statement, the hypothesis, and the research questions. The order that the thesis will follow is introduced as well.

1.1 Problem Statement

Buildings are often designed and constructed without due consideration given to how their systems will be accessed during their lifecycle. This fact can be attributable to a general lack of integration of the facility manager's perspective by the time design decisions are made (Fatayer et al., 2019; Wang et al., 2013). Also, the project delivery method and its associated timeframes for the participants to get involved (i.e., often subject to money availability or urgency to finish the project) (Zhu et al., 2018). Besides, the gap of maintainability knowledge obeys the unintended omission of access for maintainability restrictions and the complexity of the design, which possesses priorities on other aesthetical and spatial needs (Fatayer et al., 2019).

The Operation and Maintenance phase is the longest stage in any building lifecycle and accounts for almost 80% of any facility life cost (Rounds, 2018). Good practices and procedures taken into consideration and directed towards this stage can alleviate further efforts to execute physical interventions that represent resources, which might be directed to execute other operational tasks. Those practices above fall into the “Design for Maintainability” approach, which is not other than an effort to integrate the design and construction knowledge with the facility management perceptions at the early stages of any project execution.

According to the US Department of Defense (2005), maintainability can be defined as “The ability to maintain an item to be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair.” The execution of maintainability itself requires having enough room to access equipment in different positions without compromising or affecting the performance of adjacent components or systems (Liu, 2012; Liu & Issa, 2014, 2016)

Coordination can be defined as the collaborative procedure between the design and construction stages of a project, in which the representatives of different building trades get together in order to review and discuss design interferences among their systems. Leite (2019) defines design coordination as “the process of ensuring integrated design between various disciplines involved in creating a facility, be it a building, infrastructure, or industrial plant.” This process attempts to reduce rework, interruptions within the crews on-site, and over costs associated with destructive interventions. Moreover, it foresees the performance of appropriate reallocations of systems when needed and has become determinant in complex facilities “where building services need to be installed in relatively confined spaces” (Leite, 2019). The invention of digital tools in the construction industry has drastically shifted how coordination is executed. (Khanzode et.al., 2008; Korman, 2009; Korman et.al., 2008)

Building Information Modeling (BIM) and its 3D object representation of the elements of a facility set a scheme to visualize and review accessibility for maintenance during the design stage, specifically through the performance of BIM coordination. This collaborative procedure overviews the system's disposal within the building envelope to guarantee an effective integration of trades without disruptions and considering design constraints. However, not all current coordination practices are effective in terms of productivity, exchange of information, and conflict resolution and tend to set aside end-user notions that include the accessibility to the built environment.

A BIM coordination procedure that introduces facility management criteria as an additional discipline of the interferences revision and follows a sequential approach was introduced by Sierra-Aparicio et al. (2018). This research indicated that the inclusion of those additional restrictions would ensure the long-term building integrity and a reduction in the costs attributable to workspace interventions that were not visualized during the design stage. In order to bridge the gap between the design and operation stages and demonstrate the findings of that effort, this research attempts to automatically introduce specific clearances around BIM objects, enabling their recognition of clash detection tools and, therefore, highlighting their coverage during the BIM coordination execution. Current BIM authoring tools do not count with a visible component that eases this rule consideration while performing design reviews, as highlighted by Liu (2012).

The active development of the described component might allow the inclusion of end-user accessibility compliance as part of the framework scope. Up to date, individuals with restricted mobility still face some issues when moving and interacting within the built environment. “Accessibility audits by disabled people’s organizations can encourage compliance” (Organization & Bank, 2011). With an accurate framework definition, Americans with Disabilities Act (ADA) restrictions and rulesets are plausible to be incorporated in the coordination process. Therefore, the disposal and availability of spaces might be subject to revision and correction at the design stage.

Design for maintainability can be approached by establishing a framework in which maintainability constraints can be incorporated into BIM authoring software automatically, in the form of warnings or reminders. To effectively perform this task, the use of data that is already contained within the BIM model and gives a spatial notion of the location of different objects is essential. This structure might constitute a supporting decision-making tool that can set the grounds to reach an as-built BIM model, which is the starting point to learn the actual facility condition and to use the BIM model for other analyses further. This thesis will propose a proof of concept that will create the required clearance within objects in order to allow its recognition using clash detection tools, providing maintainable infrastructure as a result of the review of coordinated models (Eastman et al., 2012). A tool that provides a typical environment to share the knowledge of facility managers and designers has been previously addressed in the literature (Kalantari et al., 2017).

1.2 Statement of the Hypothesis or Research Questions

In this section, the research hypothesis and its related questions are introduced. These provide an overview of the answers this research attempts to cover and further develop.

- Is there a way to retrieve and make visible access for maintainability restrictions on already existing BIM authoring tools?
- How can this translation be effectively done?
- Are there any other similar approaches that relate to the flow of information between the design and maintenance phases?

- Can visual programming tools define relationships and create algorithms that can be used to generate geometry in 3D space and to process data for FM functions in BIM coordination?
- How can ADA compliance be incorporated in the proof of concept execution and revision?

1.3 Significance of the Study

The contribution to the body of knowledge of this proposal relies on integrating maintainability criteria on the execution of a BIM Coordination procedure. This specific merge has not been performed in the past. It expects to provide owners, contractors, and BIM managers with a clear baseline to enhance user-based decision-making while performing design coordination. Revisions to be performed include accessibility tasks to be accomplished by the facility management team and the potential consideration of code restrictions as part of an automated proof of concept. Also, there is room to develop the rules derived from a specific building case by using an already defined repository of good practices, standards, and on-site experience. Expected results might include an earlier and better approach to disabled individuals by considering the issues they daily face within the built environment or even developing OSHA's confined spaces compliance check during coordination. This way, the project's stakeholders are making sure that the integrity of the workers and occupants is considered earlier in the design and planning process and can reduce their overall exposure.

1.4 Research Objectives

The research objectives are listed below:

1. To overview the current state of the art of pre-construction coordination and the consideration of access for maintainability in the coordination efforts.
2. To ease the identification of clearance equipment constraints for further access using BIM.
3. To introduce a proof of concept that introduces equipment accessibility restrictions on BIM authoring software and translates them into elements, which can be accounted for in the clash detection procedure.
4. To discuss the elements of economic feasibility and business plan that are relevant for the future development of this prototype.
5. To define a framework for including these restrictions for retrofits and new construction projects.

1.5 Delimitation, Limitations, and Assumptions

1.5.1 Scope

The proof of concept is limited to the translation and verification of accessibility for maintenance functions that were addressed by Liu (2012) in her thesis questionnaire: lack of equipment accessibility.

This proof of concept will set the grounds for preventive maintenance execution, being accessibility a prerequisite to perform repair, replacement effectively, and cleaning tasks.

The proof of concept might be extrapolated to the execution of ADA revisions, which include room to perform movement within spaces.

Soft or clearance clashes, attributable to spatial tolerances or minimum circulation, accessibility, and maintainability clearances, will be covered.

1.5.2 Purpose

The purpose of this thesis is to set the framework that requires variables and parameters to execute a proof of concept using a Dynamo file to link Revit and Navisworks. The system will warn users of incorrect allocation, code violation, or spatial constraints that are not followed during the coordination stage by sending accessibility restrictions and minimum clearances that the equipment needs to perform maintainability revisions further. The proposed tool will allow the design of a building that supports future repairs and maintenance tasks.

1.5.3 Thesis Statement

The early detection of access for maintainability constraints during design can be eased by incorporating those restrictions in the coordination procedure. This thesis will develop a proof of concept using visual programming, to make visible maintainability restrictions at BIM authoring and support tools and add them to the clash detection overview. Consequently, the gap of knowledge between the design and maintenance phases of a construction project will be reduced, making that expertise available when designers need it the most. Additionally, there is room for introducing ADA compliance restrictions using the proof of concept principles.

1.5.4 Organization of the thesis

Chapter 1 introduces the lack of consideration of maintainability matters during a project design stage, introduces the research motivation and questions, scope, and provides the thesis statement.

Chapter 2 provides a detailed literature review, which highlights the integration of coordination and code compliance as a plausible solution to the issues addressed in Chapter 1.

Chapter 3 focuses on accessibility to perform maintenance tasks, how it is addressed in practice, which software solutions have partially addressed it as a global approach, and how scholars have managed to include it by introducing alternative software modifications.

Chapter 4 describes the research methodology that was carried out in order to come up with maintainability scenarios that are subject to potential review on a specific project. Dynamo scripts that can be extended to perform further maintainability reviews were developed. Moreover, this chapter explains the development of a coordination procedure that addresses maintainability concerns and how that concept can be materialized using existing software solutions and automating their functioning principles through a Dynamo script.

Chapter 5 explains how a further parametrization and scalability of the proof of concept to other code reviews might end up in the development of a Revit plug-in. This tool is expected to send warnings and pull up rerouting alternatives to improve the decision-making process. In this chapter, the technology development plan, drawbacks, and potential competitors are introduced as well.

Chapter 6 summarizes the findings and limitations and poses conclusions under the light of the research objectives. It also discusses further directions that this research could take.

CHAPTER 2. LITERATURE REVIEW

This chapter provides an overview of how maintainability can be addressed at the early stages of a construction project. It also introduces current applications of BIM in coordination and facilities management and justifies the importance of finding a way to link both procedures.

2.1 BIM

Building Information Modelling (BIM) is a digitalization process of the work executed in the architecture, engineering, construction, facility management (AECFM) industry, whose implementation requires changes in collaboration within participants, technology, and practices. More than a 3D software visualization platform, BIM allows the retrieval of data attached to a construction project throughout its lifecycle, which can be further used to perform simulations, constituting an informed and more landed decision-making instrument (Golabchi et al., 2014; Edirisinghe et al., 2017; Yoon et al., 2019). This statement puts in evidence BIM's underling potential to complement, correct, and embrace a better execution of construction projects in terms of timely completion, lower construction cost, quality, and waste reduction (Sacks et al., 2018b). That is why different countries around the world require its use in bidding for public projects, such as the United Kingdom, which demands a BIM Level 2 compliance to any company that wants to get involved in a government project. On the same lines, Singapore has established a roadmap to use BIM for both facilities' maintenance and smart cities. The United States does not account for a government mandate to use BIM, despite having implemented BIM earlier than other countries. Each state has defined its rubrics for BIM implementation.

Nonetheless, a consensus has not been reached in terms of standardization and practice for the whole country (Paul, 2018). Other countries highlighted in Chapter 8 of the BIM Handbook's 3rd edition, such as Norway, Finland, Italy, Spain, among others, also have Government BIM mandates.

Multiple authors have acknowledged the use of BIM for different foci during design and construction. Some of the late BIM applications are oriented to increase awareness in terms of occupant needs and specifications. Studies such as alternative routes for fire evacuation (Choi et al., 2014), path planning for identifying indoor routing patterns (Lin et al., 2013), execution of BIM code compliance checking to verify the conformity of designs with existing regulations (Preidel & Borrmann, 2018), among others, are proof of the unexplored BIM potential to upgrade the tenant's experience on the facility. Other BIM applications that have been used during pre-construction include mechanical, electrical and plumbing (MEP) coordination (Korman, 2009; Korman et al., 2008; Leite et al., 2009; L. Wang & Leite, 2014, 2016; Yung et al., 2014) and code checking compliance (Choi et al., 2014; Fan et al., 2019; Nawari, 2012; Preidel & Borrmann, 2018; Salama & El-Gohary, 2011)

BIM is the vehicle for correctly executing Integrated Project Delivery (IPD). This project delivery method relies on the integration of systems, people, and procedures from the early stages of the project, in order to determine the interdependencies among teams effectively. Also, it helps to determine the exchanges of information and address conflicts and rework when those do not represent high monetary values, in comparison with other stages of the project lifecycle. BIM as a centralized repository of the project development constitutes the only way to collaborate in a transparent environment, where all of the modifications of the trades can be observed, and recommendations within project stakeholders can be provided.

2.2 BIM In the Building's Lifecycle

The development of Building Information Modeling (BIM) has drastically shifted how projects are conceived, coordinated, executed, procured, and maintained. Besides 3D visualization and simulation, BIM allows the introduction of geometrical, spatial, and material information linked to each building system. The use of this data in different BIM support tools contributes to a better assessment of the project development by incorporating additional variables. These variables are inherently linked to the project lifecycle but not entirely included in the BIM authoring tools, such as construction sequencing, costs, sustainability, operations, safety, among others (NBS, n.d.). The consideration and integration of these variables reinforce BIM's underlying potential to complement, correct, and embrace a better execution of construction projects in terms of the time of completion, cost, quality, and waste reduction.

The data introduced in the BIM model is continuously evolving, and project stakeholders can use it for different purposes throughout the project lifecycle. Nonetheless, the BIM model is as accurate and complete as its developers wanted it to be depending on its further use. This momentary approach removes feasible long-term purposes that the model data could play at other project stages and leaves room for the avoidance of end-user specifics. Therefore, it becomes essential to determine the desired level of detail (LOD) of the models at the beginning of the project so that their information can be used for the intended purposes. Usually, these specifics are addressed in the BIM execution plan

(BEP), where all considerations of deliverables, exchanges of information, templates, legends, naming conventions, and other requirements of the BIM models for a project are addressed.

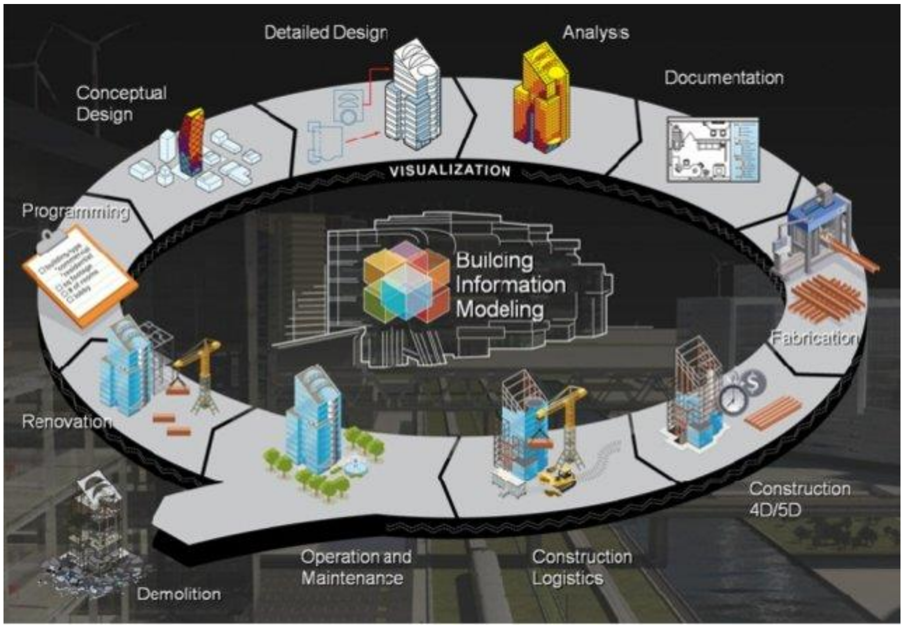


Figure 1 – The daily life of Building Information Modeling (BIM). (Dispenza, 2010)

2.3 Coordination in Construction Projects

Coordination can be defined as the correct allocation of all the systems of a facility before construction. It takes place during the design phase and requires the execution of collaborative meetings in which project stakeholders take a glance at interferences between systems and decide on their resolution, based on their design constraints, constructability, and space availability. The number of systems and their complexity increases the level of difficulty when performing coordination (Korman, 2009). This fact is attributable to common dependency scenarios between trades, in which the designs of trade might affect the routing of another, breaking the integrity of the project (Porwal & Hewage, 2013).

Adewale (2016) states that the increasing building complexity and the specialization of professionals involved during the design stage requires an integrated approach of the building design through coordination. Therefore, interferences and omissions are identified before they reach the construction site and become waste.

Project information has been historically shared using 2D drawings, and coordination was held by overlapping 2D drawings of specific portions or zones of the project to evaluate. The detection of interferences used to a time-demanding process, requiring numerous iterations and revisions as designs evolve. Coordination using 2D drawings affected the productivity between the design and construction phases of a project, due to the generation of out of date versions that hinders the communication between the project stakeholders. This issue had an impact on the flow of information between project participants as well. Moreover, 2D coordination did not guarantee a total, and accurate revision of interferences since the interferences in depth are not visible using drawings and, as a consequence, unintentionally omitted (Giel & Issa, 2013). Users require further visualization capabilities to quickly find the information and recognize interferences other than the physical ones (Korman & Tatum, 2001).

2.4 BIM Coordination

With the development over the past three decades of a computing platform that supports communication among construction project stakeholders, the on and off-site productivity has improved. As stated by Autodesk, BIM, “is an intelligent 3D model-based process that gives the construction industry the insight tools for managing a project during its lifecycle”. BIM allows an active information exchange using a BIM component called "parametric model," which is a 3D representation of the project that stores attributes for each component of the building. The use of the parametric model supports the management of the facility information before, during, and after construction. This assessment includes the revision of possible interferences of the constructive elements of the project by correcting the design problems that are presented between plans and technical specifications during the modeling process and not in the construction stage. The interference revision is performed using a federated model (i.e., one that integrates all discipline designs) on a single file, allowing multiple revisions with a clash detection tool. The success of this methodology relies on the centralization of information and the use of a standardized language that allows different coordination analysis, through iterative processes in order to eliminate interferences, conflicts, reprocesses, cost overruns and delays that might negatively affect the life cycle of a project.

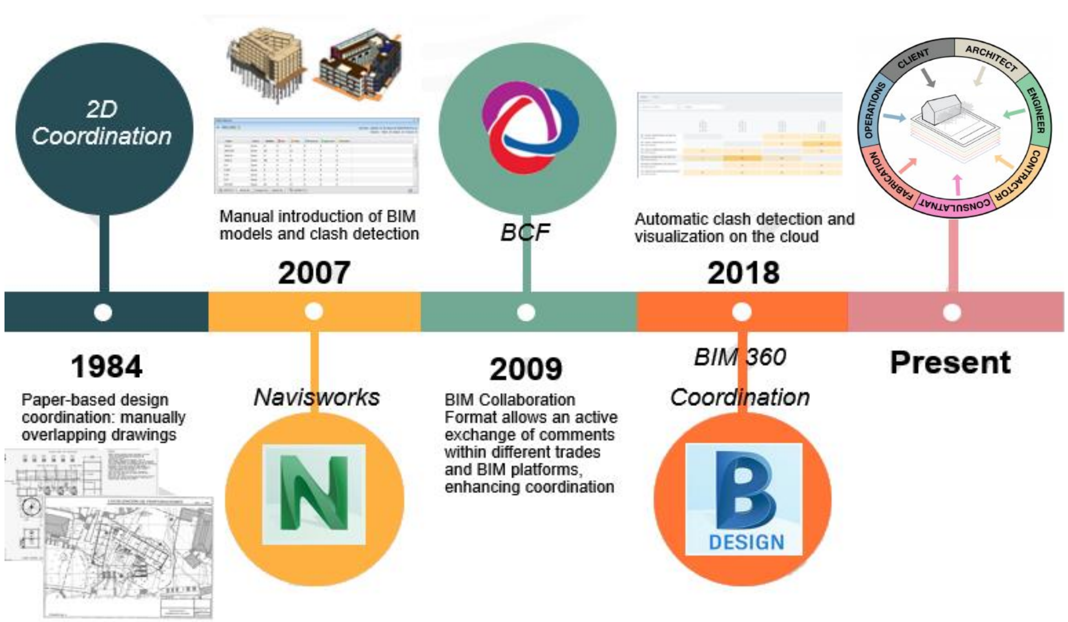


Figure 2 – Coordination Evolution

As stated in previous paragraphs, the emergence of BIM and its support tools has changed how design coordination is held. Figure 2 introduces critical milestones that are part of coordination's evolution and have allowed the integration of all project stakeholders within a federated file, which is assembled by using the models created by designers and subcontractors (Leite, 2019). In 2007, the development of Navisworks enabled the manual introduction of BIM models within a single space to perform clash detection. Two years later, a structured, filled format that enhances issue tracking by allowing an active exchange of comments and information on collisions within multiple project trades and BIM support tools was created: the BIM collaboration format (BCF). As a feature and a project lifecycle management tool of the Autodesk BIM 360 platform (released in 2016), BIM 360 Coordination was presented. With the upload of the models to the BIM 360 clouds, and automated clash detection is performed.

2.4.1 Benefits and Limitations

The generation of clash detection reports using BIM tools and their reviews on coordination meetings allows a collaborative approach towards the facility's effective functioning. It covers issues that otherwise would not have been detected. Some scholars have highlighted the benefits of BIM coordination tools in construction projects. By introducing the case study of the Camino Medical Center, Khanzode et al. (2008) pulled out the advantages of using 3D and 4D tools for different team project members. Among the overall outcomes are the reductions in the number of change orders, improvements in terms of task execution, prefabrication, and rework reductions. Wang et al. (2016) acknowledged the benefit of broader collision detection using BIM tools in comparison with the manual approach, after evaluating the Shanghai Disaster Control Centre as a case study. Bryde et al. (2013) determined that BIM coordination reduces the number of Requests for Information (RFIs) and Change Orders (COs) during construction, besides providing a reference to anticipate the subcontractor's work. After evaluating six projects, Giel & Issa (2013) highlighted coordination as an effective way to identify essential conflicts during preconstruction by addressing the reduction of RFIs and schedule overruns. Furthermore, after reviewing several case studies of BIM enabling MEP coordination, Yung et al. (2014) identified improved safety performance practices, thereby increasing efficiency and pre-fabrication opportunities as perks of using BIM for coordination purposes.

In terms of the limitations of BIM coordination tools, Bryde et al. (2013) introduced the creation of multiple file versions as a drawback. On the other hand, Khanzode et al. (2008) believed that the main difficulty of coordination is the lack of certainty at determining how the process should be managed in order to allow useful information exchange and collaboration within the project parties. The use of a centralized model itself does not bring as many benefits as desired if the project teams do not set the ground rules for exchanging information and deciding on the issue, depending on the type of interferences and constructability matters. Commonly, some trades are not willing to make changes to their designs because that might represent additional costs and efforts that they did not examine earlier. With this in mind, other authors have explored different coordination approaches to enhance the productivity of this iterative and time-demanding task.

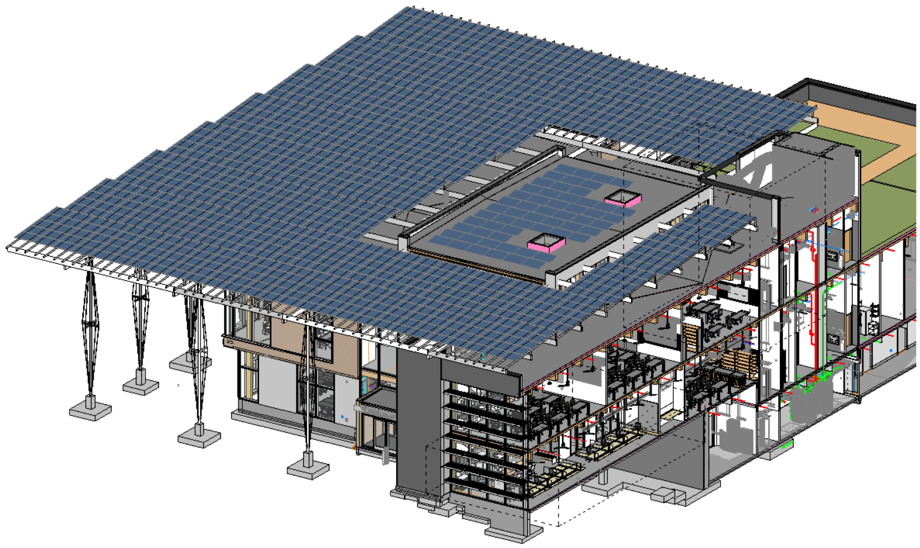


Figure 3 – The use of BIM models enables the coordination of multiple trades

2.4.2 Coordination Approaches

Korman et al. (2008) determined that MEP coordination must follow a hierarchical procedure, starting from the biggest and stiffest system to the smallest and most flexible one. Khanzode et al. (2008) reached a similar conclusion after developing a case study, noticing that rework during coordination is eliminated by following a sequential process and not a parallel one. A sequential process requires the establishment of a ranking that indicates when and which party can enter to perform modifications within their BIM models. This way, chains of circular changes are removed because all the project stakeholders align themselves to pre-established criteria and understand which design possibilities are within their boundaries, based on already coordinated systems. This hierarchy conclusion reached by Khanzode et al. (2008) is supported by Lee & Kim (2014). They found out that sequential coordination is three times faster than parallel coordination, after executing a case study on a pharmaceutical building. Leite (2019) recognizes as well that sequential coordination helps to prioritize and to define an order in which elements will be coordinated, reducing rework. On the contrary, in parallel coordination, some solutions for a trade on a specific zone might cause a ripple effect in subsequent zones.

Other scholars have covered the role of BIM coordination for constructability reviews. Wang & Leite (2016) defined a framework to apply BIM coordination until the construction phase in order to complement and validate the on-site installation process. The authors proved that this effort helped to cover constructability revisions. On the same lines, Seo et al. (2012) underlined the importance of establishing ground rules in terms of intervention, document management, and flow of information. The authors performed a detailed evaluation of clash detection at the construction phase by determining the workflow of hard clashes, soft clashes, and change orders with their respective objectives, responsibilities, and outputs. According to them, a systematic clash revision method is required to perform BIM-based constructability reviews better.

In terms of better opportunities for the BIM coordination procedure, Akponeware & Adamu (2017) recognized the need for a proactive clash detection approach to avoid siloed decisions and promote integration and collaboration towards the project benefit. The authors performed a quantitative clash detection approximation, and among their findings is the need for early engagement of all project participants in the design processes. Moreover, and in order to proactively perform clash detection, editing access to the central file must be granted via a built security manager. Mehrbod et al. (2019) addressed as further research the influence of the degree collaboration attached to a project delivery method in the number of interferences found. A study of that magnitude might highlight room for improvement in the way coordination is carried out, depending on the contract and the integration of the construction parties. Last, Ospina-Alvarado et al. (2016) analyzed the perceptions of different AECFM industry individuals towards the issues that determine the achievement of integrated projects. In that classification, the early involvement of key project participants was ranked among the critical success factors, implying that when the input of knowledge and expertise is incorporated in the earliest project stages, the decisions based on those besides being informed, are less costly. By introducing the notions of the facility manager during the coordination procedure, future destructive interventions and displacement disruptions are avoided.

Besides covering different methodologies, BIM coordination has been addressed by different software vendors that seek to improve how information is presented, handled, and shared, once extracted from the clash detection tool. Those solutions include clouds, plug-ins, and issue managers.

2.4.3 Current State of BIM Coordination Tools

2.4.3.1 Navisworks

Navisworks is an Autodesk product aimed to improve coordination. It allows the integration of Revit models from different disciplines to generate clash and interference reports further while having 4D simulation capabilities. Its major drawback is the limited access to updated information since everything is concentrated within a single file. Also, interferences cannot be tracked back, and it is not possible to discuss issues other than relying on the central file.

2.4.3.2 BIM 360 Glue

BIM 360 Glue is an Autodesk cloud service integration tool. This platform allows the creation of a cloud-based and up to date interference revision between RVT, DWG, and Industry Foundation Classes (IFC) Revit models. After the upload of all BIM models, it automatically performs clash detection. It makes visible the total number of interferences using a matrix form, but it does not suggest a hierarchy for their resolution. This cloud-based approach enhances collaboration between the project stakeholders from any part of the world, just using smartphones or tablets.

2.4.3.3 BIM Track

BIM Track is a web-based platform that supports different BIM authoring software and optimizes communication through the use of Open BIM standards. It allows the creation and assignment of incidences and their revision out of the authoring software. All parties involved are capable to trace the evolution of the project, reviewing which changes have been made and enhancing the collaborative process. Moreover, all the project information can be accessed from any device.

2.4.3.4 BIM Collab

BIM Collab is a BCF issue manager that can be added to different BIM platforms in the form of a plugin. It allows the overview, filter, and assignment of issues to promote an effective exchange of comments and information between project stakeholders. The information on the projects can be visualized through the cloud. Once all the issues are complete, BIM Collab sends a notification to the interested parties, enhancing the workflow towards the project.

2.4.4 BIM Coordination Gaps

BIM Coordination is mostly focused on the design and construction phases of a project. As introduced above, on the design phase, it is used to oversee potential interferences that might arise during on-site execution. During construction, it is used as a source of validation and correction. That usage depends on the issues that have emerged at the time. However, coordination itself has not been targeted for operation and maintenance concerns. Korman & Tatum (2001) determined that an absence of communication between designers, constructors, and operation personnel hinders the integration of operations and maintenance (O&M) knowledge in the coordination procedure, leading to posterior difficulties such as rework and out of date information. On the same lines, Bahadir & Arditi (2019) have identified that maintainability is not considered at the early stages of the project, and this implies cost overruns during the latest building lifecycle stage that obey not considered clearances. Adewale (2016) highlighted that the main objective of coordination is ensuring that materials and equipment are prevented from physical conflicts or from impairing the installation of other systems within. However, often priority is given to usable spaces only, allocating the shorter room to MEP configurations and machine rooms.

Construction still lacks the synergy of teams at the early stages of the project development, and most of the time, this is attributable to the project delivery method that is chosen to execute the work. For instance, in the design-bid-build approach, the builder is not chosen until the design is completed, and constructability is usually avoided. In the design-build case, design and construction are carried out in parallel to accelerate the development process. Nevertheless, most of the design issues are covered directly on-site, and it is more feasible to avoid operation and maintenance criteria while focusing on complying with the desired schedule. In contrast, the integrated project delivery (IPD) method determines that high-performance buildings are the result of the constant feedback from the construction and facility management representatives during the design execution, constantly modeled by the end-users' value definition.

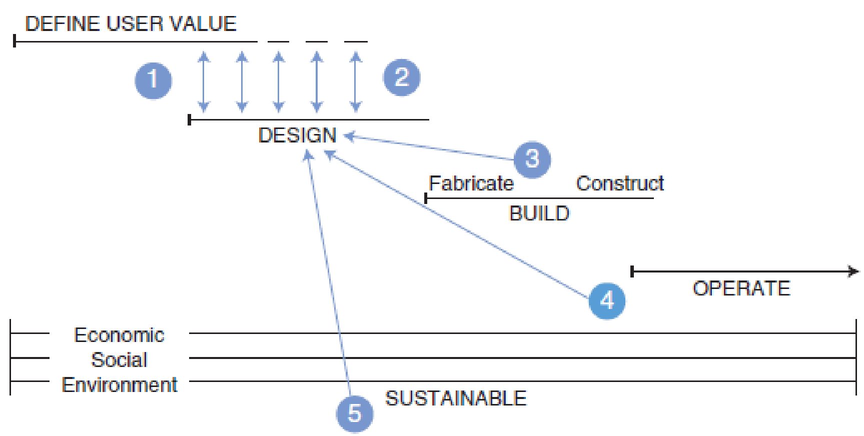


Figure 4 – The five main types of process integration to achieve high-performance facilities. Reprinted from "Integrating Project Delivery," by Fisher et al., 2017, pg. 117

There is a paucity of the literature examining or determining how a more comprehensive tool can be conceived in order to address maintainability concerns during the design stage. A few years ago, Liu (2012) and Liu & Issa (2014) developed an add-in solution on Revit that allowed the creation of a clearance box within the equipment that required accessibility for maintenance. The authors highlighted that further coverage of the tool was needed. Bahadir & Arditi (2019) also addressed the need for an appropriate tool to detect and solve potential maintainability problems during the design stage and defined a framework to develop it. Both statements highlight the importance of understanding the user's relationship with the built environment while performing coordination.

2.5 BIM for Facility Management Applications

Even though BIM functionalities and its applications in the built environment are still undergoing research, some authors argue for the potential of BIM to support facility management tasks. Extensive literature reviews, like the one conducted by Gao & Pishdad-Bozorgi (2018), identified trends of BIM applications in building operation, maintenance, and repair, and highlighted gaps in understanding the workflow of FM processes and how those can be related to BIM. Alike, Ilter & Ergen (2015) clustered research topics in four big groups, established continuity relationships between undergoing and past research, and concluded that further review of interoperability needs to be done. Moreover, Edirisinghe et al. (2017) reviewed and categorized numerous research articles, identified research trends, and concluded that despite interoperability between software solutions has been explored; data capture techniques are still lacking. Kassem et al. (2015) attempted to determine the challenges and values that came along with BIM in FM applications and concluded that there is a lack of interoperability and standardization issues that may allow data transfer from BIM to FM platforms. Last, Aziz et al. (2016) reviewed the BIM in FM applications that influence the workplace's quality of life (QOL) and concluded that retrieved data could be further used and directed to perform facility management tasks and brings benefits in the long run.

Other authors have addressed specific applications of BIM data for facility management purposes. Hu et al. (2018) highlighted the need to retrieve the information of the MEP systems for an effective assessment during the O&M phase. The authors developed and O&M management system that allows the digitalization of MEP information for further revision and usage in the O&M phase. Besides, Motawa &

Almarshad (2013) defined a system architecture to contrast information retrieved in the BIM model with a system that captures the knowledge of building maintenance cases. That way, traceability is possible by overseeing the maintenance tasks performed on existing objects.

The aforementioned breath of knowledge demonstrates that BIM has facility management capabilities that will allow and enhance a better assessment of the facility during its longest lifecycle phase. Despite this, different considerations need to be covered in order to ensure that the resulting BIM model can be effectively used in computerized maintenance management systems (CMMS) and similar structures. Moreover, the literature above demonstrates that all the effort that entails updating and developing the BIM model during pre-construction and construction stages does not end up there and can be further used in operational applications.

2.6 Accessibility and Maintainability Considerations

Facilities are long last assets that need to be constantly monitored and repaired. Otherwise, their occupant’s integrity and safety will be compromised, and the facility will no longer be able to provide the services and uses it was aimed for. The introduction of new technologies in the construction industry has enhanced a better assessment of the lifecycle information that is needed at the operation and maintenance phase. Lately, different scholars have highlighted the potential of BIM for covering facility management tasks through the retrieval and management of lifecycle information.

Specifically, on the design stage, maintainability and other facility management considerations have been addressed as tasks that can be covered using BIM tools. Zhu et al. (2018) performed an extensive literature review to determine the trends in design for maintainability efforts. The authors identified four key categories in research trends, being maintainability implementation status and barriers one of those. In this regard, the authors highlighted a gap of technologies to transfer the maintainability knowledge between design and operational phases. Fatayer et al. (2019), concluded that the integration between design and operation teams has direct benefits on the maintenance expenditure and a drop in the facility life cycle costs, after performing a series of surveys within facility management departments. According to the authors, the schematic design is the stage in which maintenance feedback is found more valuable because decisions have not been taken by that time. Kalantari et al. (2017) found out that an extensive collaboration between designers and facility managers enhances design flexibility and benefits the facility in the long run. Additionally, the authors suggested that BIM practices can be adjusted in order to promote a common environment in which designers and facility managers can thrive.

Accessibility and maintainability are within the extensive list that authors have recognized as O&M tasks that can be controlled using BIM. Ilter & Ergen (2015) highlighted the need for a maintenance assessment during concept and design stages in their exhaustive literature review on BIM for refurbishment and maintenance. Liu (2012) and Liu & Issa (2014) recognized the importance of reducing the gap between design and maintenance by incorporating an accessibility checker that helps to identify unfriendly design issues that can further reduce the cost of maintenance, affecting the life cycle cost of the facility as well. Leite (2019) determined that BIM models can be upgraded to the LOD needed for constructability reviews during the design stage by adding clearance zones and access paths. Examples of clearance zones are the ones required to open double swing doors, as shown in Figure 5.

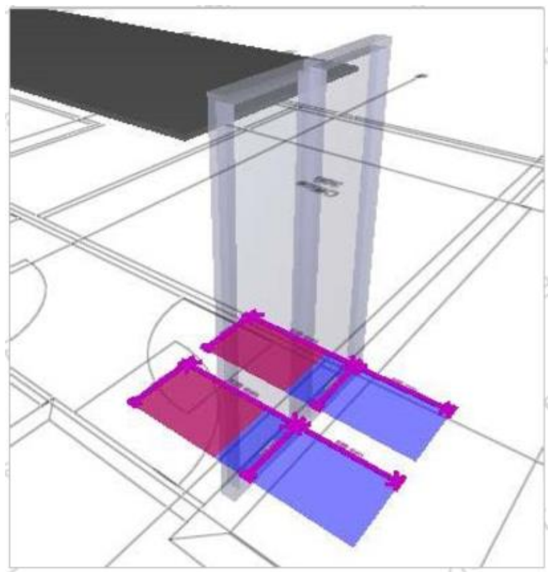


Figure 5 – Opening space of a door (Ferreira, n.d.)

2.7 Code Compliance

An important part of the design execution is the compliance revision with building codes and standards that are specific for the facility considered. In practice, this revision tends to be executed once construction documents are completed, and project construction has begun. One of the applications that have emerged with BIM is the feasibility of using the model for code compliance revision during design through BIM support tools, such as Solibri Model Checker. These tools allow the manual introduction of rule sets that reflect the restrictions addressed in the normative. Figure 6 introduces a summary of the steps required to perform a code compliance review. It starts by preparing the BIM model for checking, making sure that all the elements required to perform the check are present within the 3D environment. After this, an identification of the types of checks that apply needs to be done. Not all rules can be translated from a human to a machine language, and this needs to be considered. Also, some rules can be programmed to apply in a hidden environment, while others require the input of the user. The next step is identifying the portion of the project that needs to be checked since focusing on a specific portion eases the error detection. The last step is reporting the errors and fix them in the authoring tool so that the support clash detection tool will perceive a reduction in the number of interferences.

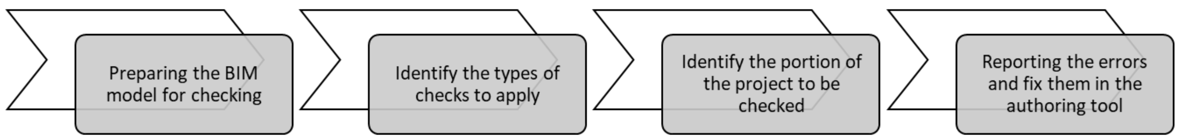


Figure 6 – Code compliance workflow

The use of code compliance as an application of the BIM model has demonstrated to bring benefits to the model revision. Cavka et al. (2017) developed an evaluation of the owner requirements by performing compliance revisions on the BIM models, including the overview of the model structure, data accuracy, and design compliance that further strengthens facility management practices. This contrast between the owner requirements and what is retrieved in the BIM model helps to identify missing pieces of owner-valued concerns. As a consequence, it sets a baseline to complement a design that meets pre-established needs. Solihin & Eastman, (2015) introduced a four-class categorization of rules in which they identified specific cases from the literature and their requirements depending on the type of rule, how can those be implemented, and the steps required to comply them. Moreover, the authors highlighted the potential usage of already created rulesets in the revision of specific domains. Lee et al. (2015) used a BERA language to evaluate relationships between spaces in terms of accessibility and visibility. The authors emphasized that the use of rule checking tools enable better coverage of predefined requirements for further revision and approval.

Other authors have addressed the limitations of using code compliance tools. Sanguinetti et al. (2012) highlighted the need for a pre-checking of screening operations to inform the user of the types of analyses that can be supported with data available in the current base model. Such a case implies the verification of existing data that supports the verification of the code compliance restrictions already predefined. Also, Nawari (2012) found out that not every part of the codes and standards can be computerized, and a previous recognition of this must be exerted before incurring unnecessary efforts. The same author concluded that not all the knowledge could be represented as needed in existing rule checking engines, leading to potential errors. Salama & El-Gohary (2011) underlined that most existing automated compliance checking tools are incapable of executing multiple levels of reasoning and checking that include compliance with contractual requirements. Preidel & Borrmann (2018) identified that the correctness of the results of a checking process is highly dependent on the correctness and availability of the information in the underlying BIM model. Therefore, a previous revision of the accuracy and consistency of the data contained within the BIM model is mandatory.

A wide breadth of case studies shows the use of code compliance tools in order to enhance the rule consideration and revision using BIM tools. Zhang et al. (2013) developed a framework to automate the revision of fall protection requirements in order to provide a tool that eliminates hazards and oversees the safety and integrity of laborers, allowing the overview of safety schedules as a part of the safety planning alternatives. Fan et al. (2019) performed a case study to introduce an end user-based rule interface that provides the flexibility to review the influences of introduced designs changes, through the retrieval of rule violations and their associated elements. Di Giuda et al. (2020) visualized and developed a tool that allows the performance of clash detection revisions and its capable of returning collisions reports that are accompanied by an alternative way of resolution. Lastly, Singh et al. (2015) performed a study focused on the use of parametric modeling through visual programming in order to develop rule-based objects to associated Modular Coordination to assists designers during the decision-making process.

Different algorithms and performance-based issues can be evaluated using rule checking tools, and those restrictions can be either introduced by the user or pre-defined by the system in place, as mentioned in previous paragraphs. With this in mind, this study will evaluate the feasibility of a Dynamo file that identifies maintainability constraints during the performance of coordination. In other words, a coordination and code compliance proof of concept will be developed as a part of the BIM authoring environment. This program is an effort towards a code compliance focus that foresees accessibility requirements using BIM coordination.

2.8 BIM Coordination oriented to Facility Management

Information exchanges are a critical part of the coordination procedure. If those are not adequately established at the beginning of the project, they might pose complications that include the omission of interferences that usually end up in destructive interventions and waste on the construction site. Khanzode et al. (2008) highlighted the importance of considering information exchanges as the starting point to structure a coordination procedure since the proper access to updated information determines a baseline to decide further actions to follow. The BIM Essential Guide for Collaborative Virtual Design and Construction (Building and Construction Authority, 2013) introduced incremental coordination in the form of a matrix as a way to promote an efficient model handover and data visualization and interpretation between the project stakeholders. The matrix is based on the space allocation suggested by Korman et al. (2008), which gives precedence to the architectural and structural trades, followed by the MEP systems.

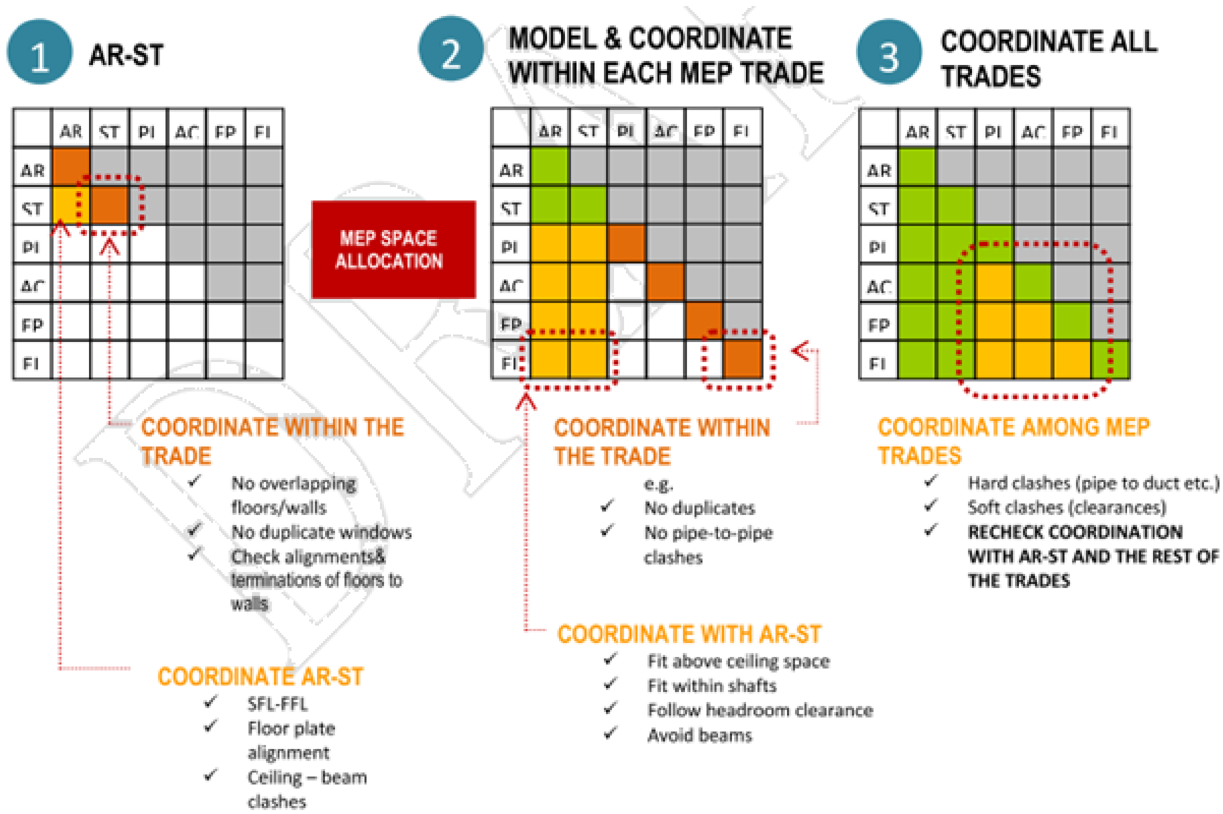


Figure 7 – Incremental Coordination. (Building and Construction Authority, 2013)

Figure 7 provides an overview of the Singapore BIM Essential Guide matrix. Each intersection within columns and rows represents the number of interferences found within those trades using the clash detection tool. The main diagonal represents the unresolved inter-discipline interferences attributed to the same discipline objects or duplicates.

Everything below that diagonal is the interferences within multiple trades. The suggested methodology starts by solving the interferences of each system with itself and continuing with the interferences with other systems until the system that is subject to evaluation is coordinated. Therefore, coordination is always performed under the main diagonal and until each column is fully coordinated. The set of a hierarchy of intervention is a more effective, automated, and prearranged way to make all parties aware of the time in which they should enter the coordination procedure, by considering the disposition of already coordinated systems. A hierarchy definition helps to prioritize and create an order in which the elements will be coordinated because all trades are working in their scope of work. The last is based on previous scopes in the hierarchy that are already coordinated (Leite, 2019)

Sierra-Aparicio et al. (2019), identified the need for a baseline definition in terms of routing and space criteria that are respected by all the project trades in order to warranty a more effective and less time-consuming coordination process, after performing coordination in various real estate projects. With a thorough literature review, the authors came across the BIM Essential Guide for Collaborative Virtual Design and Construction (Building and Construction Authority, 2013) proposal. They learned that coordination could be structured in a way that circular changes are avoided, and everyone has access to the information when needed, so routing alternatives or feasible solutions for a trade are covered with the certainty that other parties will know when to intervene and how. Additionally, from the literature overview the authors found out that the attention to coordination is mainly posed in MEP systems due to their complexity and room restrictions. No attention is given to maintainability and accessibility restrictions as a part of the coordination procedure, which are determining requirements by the time the building is handed over to its administrator.

This type of restriction is defined by Korman & Tatum (2001) as future interferences, in which the space required to perform routine operations is not efficiently allocated towards equipment. Seo et al. (2012) and other authors address them as soft clashes, which hinder the access and distribution of other components within the built environment. Tommelein & Gholami (2012) refer to soft clashes as the clearances required for systems coordination during design. The inclusion of soft interferences attributable to accessibility clearances to perform maintenance tasks as a discipline of the coordination matrix was introduced by Sierra-Aparicio et al. (2019) in their FM - Coordination matrix proposal. It can be detailed in Figure 8.

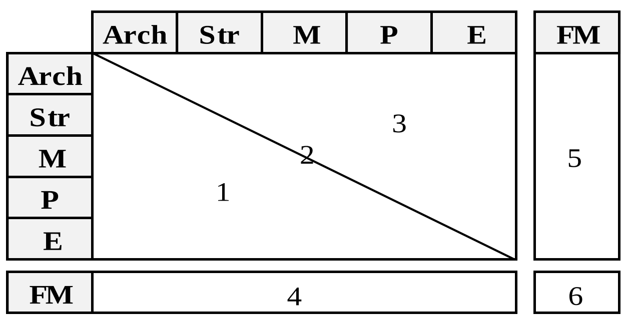


Figure 8 – The FM Coordination Matrix. (Sierra-Aparicio et al., 2019)

For the scheme previously introduced in Figure 8, the building's envelopes and structure are on the top of the coordination hierarchy, which implies that they remain as a reference point for the other trades to route and introduce their systems. This issue resembles the traditional BIM Coordination matrix (regions 1 to 3) and adds a facility management portion conceived by the authors, which covers regions 4 to 6. Regions 4 and 5 refer to additional accessibility revisions that are attributable to each discipline. For instance, in the architecture and facility management region, the entry room that a maintenance laborer needs to effectively access the space between the ceiling and MEP systems to perform revisions will be addressed. Region 6 will comprise the prioritization of FM criteria, for example, the intersection of two clearance spaces such as a door sweep and the circular room required by a wheelchair in a bathroom scenario.

Additionally, and with the concept of the FM – Coordination matrix, the authors introduced two uses of the resulting matrix, which might further help to identify coordination trends and learn which party has executed changes in the performance of the coordination procedure. The first use was named “Color Scale” and helped to recognize the combination of trades that has the biggest number of conflicts and might require greater coordination efforts. This use also helps the visualization of how trends in interferences change through time as the most conflictive systems are rerouted and reallocated.

The second use identified by the authors is “Responsible.” It eases the recognition of the disciplines that are responsible for allocating or rerouting their design, ensuring that the systems which are given the priority can be effectively placed by satisfying already covered restrictions.

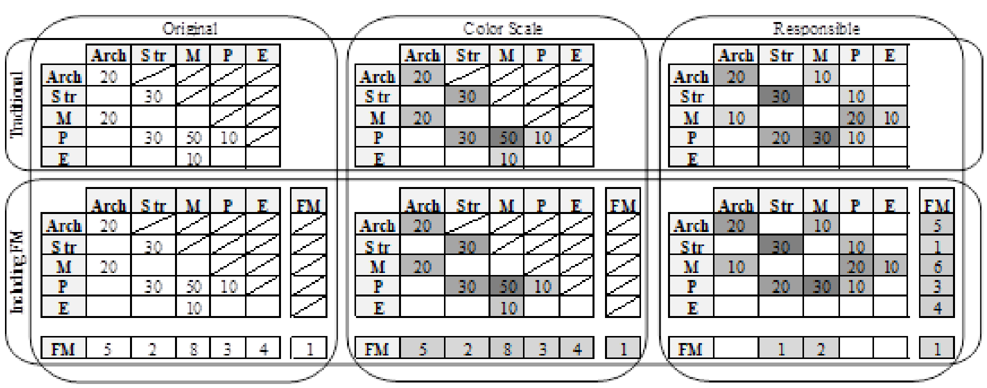


Figure 9 – Traditional and FM Coordination Matrix Contrast. (Sierra-Aparicio et al., 2019)

Table 1 – The Matrix Relationship with Proposed Uses. (Sierra-Aparicio et al., 2019)

	Zone	Original	Color Scale	Responsible
1	Inter-discipline interferences	Number of interferences among disciplines	Conflict zone (darkest cell)	Number of interferences solved by the trade of the rows
2	Intra-discipline interferences	Duplicate check	Critical intra-discipline system (darkest cell)	Auto corrections
3	The transposed version of 1	N/A	N/A	Number of interferences solved by the trade of the columns
4	FM criteria	FM requirements	Critical FM requirements (darkest cell)	Criteria conceded by the facility manager
5	The transposed version of 5	N/A	N/A	FM criteria that have been solved by the trade of the rows
6	Intra-FM interferences	FM requirements	Critical FM requirements (darkest cell)	Remaining FM criteria

The definition of an intervention hierarchy and its representation on a matrix eases the identification of responsibilities and change trends in a specific system. If the interferences above can be addressed and caught by clash detection tools, the overall clash detection process will be more accurate and will address maintainability from design stages.

CHAPTER 3. ADDRESSING END-USER ACCESSIBILITY

This chapter introduces the importance of accessibility, highlights how it has been addressed during the lifecycle of an educational facility (focused on maintainability and end-user purposes). It also introduces the importance of performing extensive accessibility checks and summarizes end-user accessibility revisions that have been performed using Virtual Design and Construction (VDC) tools.

3.1 Introduction

The ultimate goal of any facility is to provide a space in which its occupants can effectively perform their daily activities without compromising their health and well-being. These considerations are covered throughout the project lifecycle. However, they tend to be left behind on the short-term approach while making design decisions or on the daily project execution when the stakeholders are trying to accomplish the desired scope within the established timeframe and budget. This omission of end-user focus might affect the operation and maintenance phase of the project. There, most of the design flaws and unconsidered maintainability issues appear, and those demand more time and resources to be resolved. This disjoint between designers and operators is an increasing interest topic among scholars (Asmone & Chew, 2018; Fatayer et al., 2019; Kalantari et al., 2017; Zhu et al., 2018) and sets the foundation for a further review of strategies to include maintainability and accessibility during the design phase.

3.2 How is accessibility addressed during design?

3.2.1 The Kendeda Building Case

The elimination of physical barriers in the built environment enables individuals with mobility restrictions to actively take part in employment, education, leisure, and other activities. By considering all possible end-users and their needs within a space during the building´s composition, a universal design approach is reached. Different green and health building certification systems acknowledge the incorporation of equity-based practices that include accessibility, circulation, signage, and other considerations to enhance the interaction and sense of attachment with the built environment. The Kendeda Building at Georgia Tech is pursuing the Living Building Challenge 3.1 certification. One of its imperatives, Equity, was addressed with the creation of the Equity Petal Work Group, constituted by GT faculty, students, and staff, which worked alongside the project contractors and designers to explore and translate equity measures during the project's design and construction (Hirsh, 2017). In order to understand how accessibility was addressed during the project's design and coordination with the use of virtual design and construction (VDC) tools, small talk with a representative of Lord Aeck Sargent (LAS), the design firm, was held at the beginning of March 2020.

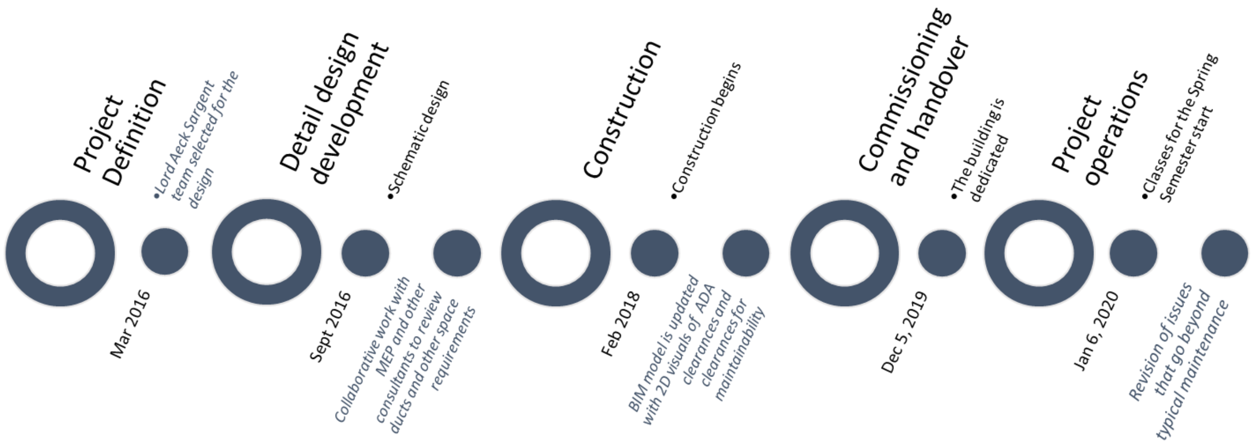


Figure 10 – Kendeda Building timeline with Lord Aeck Sargent interventions.

Figure 10 introduces key milestones of Kendeda' s lifecycle and also includes in blue the instances in which Lord Aeck Sargent took part. After being selected as the design firm alongside The Miller Hull Partnership, LAS started to brainstorm ways to guarantee universal access to the building, one of the imperatives from the Equity Petal. Merging the Eco Commons and Kendeda projects, accessible routes to the site were conceived. Almost 90% of the paths are accessible. Moreover, the ramp through the atrium (See Figure 11) is a tangible approach and grants primary access to spaces nearby at different levels. It is connected to the elevator, allowing a smooth movement within the space.

During the Schematic Design stage, the LAS team partnered up with different MEP and other consultants to work collaboratively and tackle any issue that might show up and require any type of redesign (ducts definition, clearance of specific equipment, etc.). On the post-occupancy evaluation exerted by the team, the design changes were out of the question. When asked, the LAS team representative reinforces that maintainability and accessibility issues need to be addressed from the very beginning of the project.

Figure 11 – The Kendeda Atrium. (Green & Phillips, 2019)

Coordination took around 36 months, covering both design and construction phases. General coordination considerations include:

- Tool: Autodesk 360 Glue (which requires a Navisworks introduction of all systems in a sole model. in the process).
- Participants: all trades subcontractors, design team, and general contractor team. People from the facility management team were not included.
- Meetings: all the interferences were revised using the glue model, and a particular focus was posed on the location of the HVAC systems. Those were held twice a week.
- Coordination criteria: it followed the construction documents, clash detection execution, and the revision on each item of the interferences report. Architecture and structure were left visible, and everything else was attempted to be hidden but adequately allocated. The ceiling was designed to be exposed.

- Constructability review: being a CM at-risk project, Skanska (structural designer) was in charge of performing it.
- Fire system: the subcontractor was in charge of drawing and specifying its clearance details.

For the construction stage and in order to address accessibility on the BIM model, the LAS team used 2D visual representations to show room for maneuver to perform maintainability within spaces and other ADA requirements for evaluation. All the mandatory clearances were determined using applicable codes and standards. The aforementioned visual representations are nested families, which are contained within Revit families and have attached dimensional parameters that can adapt to the object's size. Specific cases on the Revit model include the doors sweep and the creation of a clearance room that was part of the machine room of the elevator. Also, the area that determines access to the transformer in the machine room, the clearances required in front of compost bins, and the ADA clearances in front of drinking fountains (See Figure 12 and Figure 13). Also, some "blue boxes" nearby the "ceiling area" and attributable to the clearances to access mechanical elements using a ladder were observed on the Navisworks model.

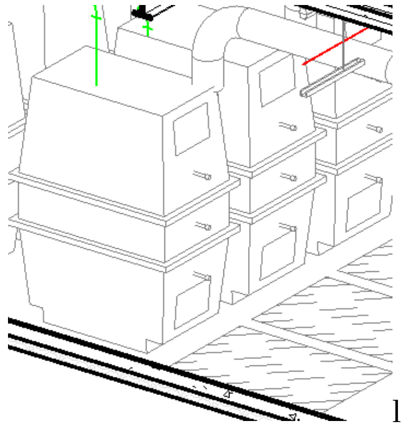


Figure 12 – Compost bins with maintainability clearances

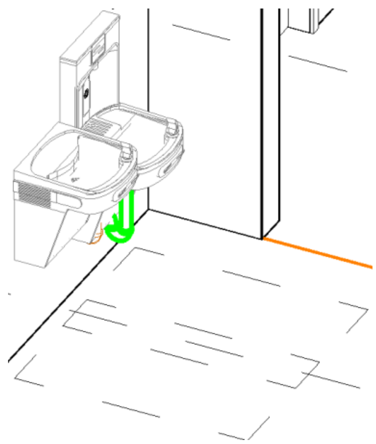


Figure 13 – Drinking fountains with ADA clearances

Up to date, the Kendeda Building is going under a commissioning phase, and the architecture team keeps being involved there, by revising issues that are greater than typical maintenance. At least one team member is once a week on the building, making sure that all the doubts are covered. Also, three members of the Georgia Tech Facilities team are currently involved in every Owner Architect Contractor (OAC) meeting, highlighting the importance of the building as a campus asset.

3.2.2 GSA

In contrast, the US General Services Administration (GSA) on its National Accessibility Program (Administration, n.d.) mentions that their Regional Accessibility Officers conduct design reviews at regular intervals during the project's evolution. To minimize accessibility concerns at later stages, those start to be addressed on the concept development phase. Figure 14 summarizes the revisions developed by each Regional Accessibility Officer. Starting from the concept development phase and going through the design development phase of a project, accessibility reviews are done according to the design level of completeness.

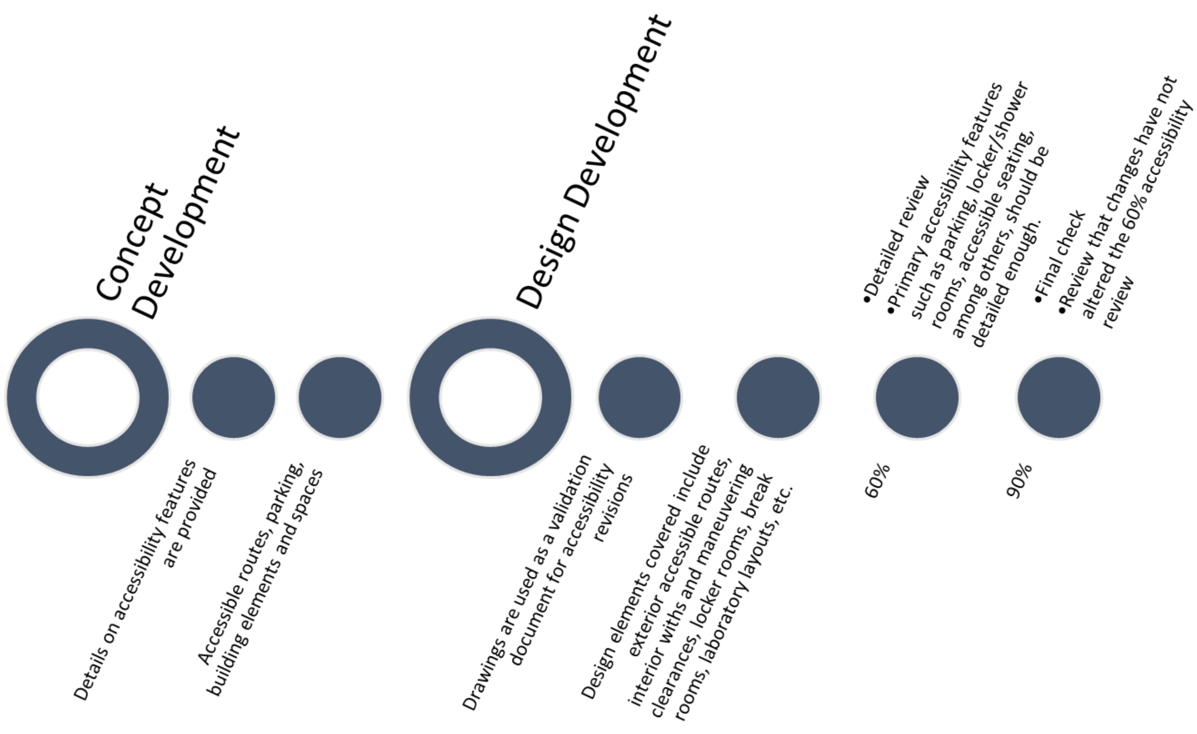


Figure 14 – GSA Design Reviews. (Administration, n.d.)

From the Kendeda building context, it is visible that the facility manager's perspective is not fully integrated at the early stages and that designers do not count on that tacit knowledge. Therefore, designers rely on the normative and draw 2D representations of the clearance spaces that need to be considered. This affirmation is supported by Leite's statement, which entails that "information in design drawings is augmented and detailed by the subcontractors, with the development of shop drawings and details needed for installation, ensuring that the engineer's design intent and prescribed system performance are maintained"(Leite, 2019, p.89)

3.3 Approaches to end-user accessibility

Existing commercial software solutions have included some of the ADA required revisions or templates as a part of their demo. Those are Solibri Model Checker and SmartReview APR, whose ADA subchapters are highlighted in Table 2. Among the revision templates available for Solibri are the accessible door, ramp, stair and window rule, and free floor space checkup (Sherrill, 2015). In addition to templates, few authors have performed accessibility revisions within their studies. Sanguinetti et al. (2012) performed a circulation assessment for the design of a courthouse by following the U.S. Courts Design Guide (USCDG) that is based on the Americans with Disabilities Act Accessibility Guidelines (ADAAG). The assessment considered three circulation zones: secure, restricted, and public. Based on those, a prearranged set of rules was run, and a report that reviewed their compliance was created.

The case study mentioned above sets the grounds for the insurance of enabling work environments that focus on accessibility and reduce negative interventions that might increase discrimination among individuals with reduced physical mobility "Experience shows that mandatory minimum standards, enforced through legislation, are required to remove barriers in buildings" (Organization & Bank, 2011)

Table 2 – ADA revisions performed by existing software solutions and studies

Software tool/study	**ADA Chapter**	**ADA Subchapter**
Solibri Model Checker	3 Building Blocks	302 Floor or Ground Surfaces
	4 Accessible Routes	404 Doors, doorways, and gates 405 Ramps
SmartReview APR	6 Plumbing Elements and Facilities	606 Lavatories and Sinks 610 Seats
Sanguinetti et al. (2012)	8 Special rooms, spaces, and elements	808 Courtrooms

3.4 Importance of comprehensive accessibility checks

The emergence and application of the ADA have improved accessibility within the public and private spaces. Nonetheless, low income and disadvantaged communities tend to suffer the burden of low-quality design and construction, which is still visible in the uplifting of new places. Those inequalities critically affect the development and well-being of individuals and entail a need for designers to examine their compositions under the eyes of the final user. Figure 15 introduces a common design flaw in terms of accessibility: the lack of space for an individual in a wheelchair to freely use a bathroom and change there with ease and dignity.

The consequences of bad design are more likely to be perceived by disabled and older people, who still have difficulties in moving and using some buildings beyond their entrances. Therefore, the input and perceptions of these individuals, if considered, can lead to an inclusive design, which advocates for access with dignity and responsiveness. Moreover, inclusive spaces are welcoming, convenient, flexible in use, and can accommodate individuals with specific requirements. (Malloy, 2014)

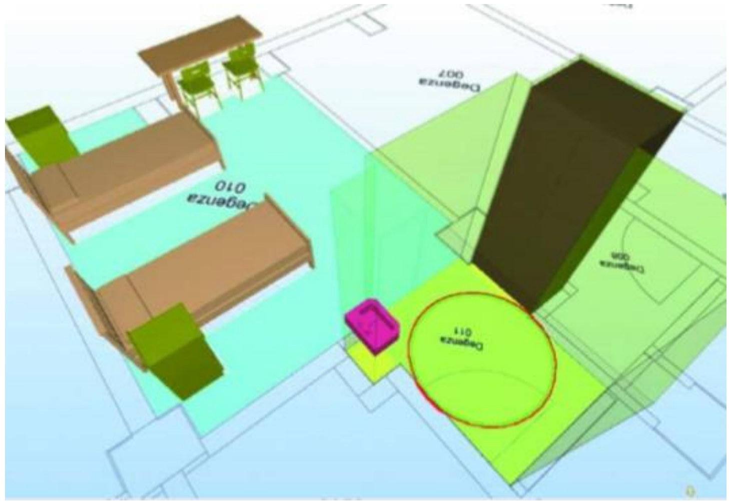


Figure 15 – Lack of space for a wheelchair spin in the bathroom. (Ferreira, n.d.)

The Guide of Inclusion by design states that “decisions about the design, planning, and management of places can enhance or restrict the sense of belonging from individuals within the built environment, stretching or limiting boundaries, promoting or reducing mobility and improving or damaging health” (Malloy, 2014). A way to ensure that the input of mobility-impaired people is considered during design is the usage of an accessibility checking tool that works as a repository of good practices. This tool might set the grounds for a complimentary revision instrument when designers do not count with access specialists capable of pointing out flaws from the concept to the post-occupancy stages.

3.5 End-user accessibility revisions with digital tools

Accessibility in the built environment using VDC tools is not a new research topic. Table 3 summarizes studies performed to improve the accessibility of individuals with physical mobility restrictions.

Table 3 – Accessibility approaches from the literature

Authors	**Title**	**Approach**	**Software/File Extension**	**Overview**
S. Wu et al. (2007)	An IFC-based space analysis for building accessibility layout for all users	Showing how BIM can reduce the time devoted to accessibility checkups (extracted from the DAA 1995) by establishing relations using the IFC model properties. There have been difficulties in translating that information into automation tools and effectively addressing design inconvenient	IFC	The IFC file properties were used to relate the existence of space and the inclusion of an element within its boundaries. All the identified information within spaces is retrieved in a matrix, and the criteria of inclusion follow the graph theory (spaces as nodes and doors or physical fragmentations as elements)
Sanguinetti et al. (2012)	General system architecture for BIM: an integrated approach for design analysis	Circulation assessment using post-processing techniques to adapt the model for specific analysis needs	IFC	Based on the circulation and access guidelines for courthouses from the USCDG, a circulation assessment to validate a concept design was made. The revision of circulation alternatives was made using predefined rulesets within a start and a target space, by considering established areas, spatial and adjacency information
Wu & Kaushik (2015)	Design for aging with BIM and Game Engine Integration Design for aging with BIM and Game Engine integration	Path planning for an appropriate and thoughtful architectural design that creates supportive environments for the elderly	Revit integrated with Unity	The authors explored the use of a game engine that facilitates the path planning of individuals with reduced mobility by executing “a collision detection between the moving avatar and the bounding boxes of a fixed building element.”
Strug & Ślusarczyk (2017)	Reasoning about accessibility for disabled using building graph models based on BIM/IFC	The search for accessible routes for disabled people that strengthens route quality in terms of time, length, and convenience	IFC	The authors introduced building-related knowledge using a graph-based representation of the buildings with an IFC approach. Accessibility relations between building spaces are computed and stored in the graph structure and provide users with feasible routes that require low efforts in traversing the space

CHAPTER 4. PROOF OF CONCEPT TOOL

This chapter introduces the steps required to conceive the tool, its working principles, inputs, and outputs. Among those are the variables and parameters that set the structure of a conceptual framework that addresses maintainability and accessibility concerns during the design stage.

4.1 Introduction

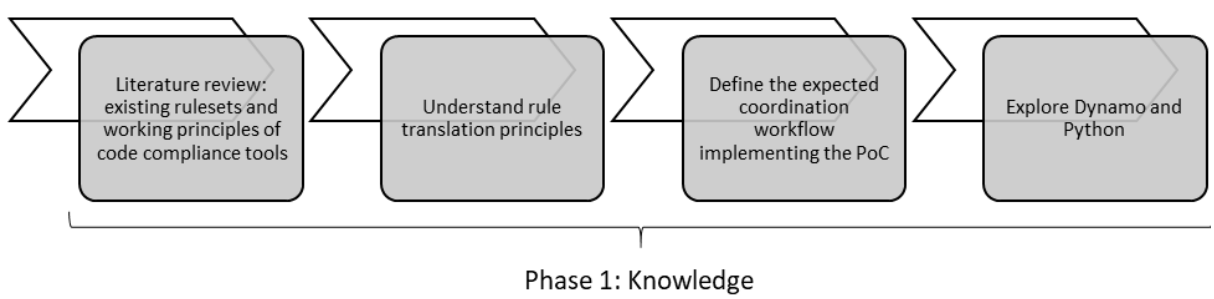
As mentioned in previous sections of the document, this research implies the development of a visual programming tool that is capable of generalizing, addressing, and showing required space for access and perform maintainability tasks, as part of the coordination procedure. To effectively perform this, certain assumptions, attempts, revisions, and evaluations needed to be made. A preliminary review of the tool requires the following steps: setting aside in a list of equipment or elements that are attempted to be reviewed and will constitute the inputs of the tool. These elements need to be adequately named and characterized in order to make a relationship with the associated objects in the Dynamo workspace.

The automated introduction of clearance boxes within Revit models will ease their detection in the class detection environment, and therefore, their consideration as design restrictions that need to be met. This fact is supported by Leite (2019), who considers that soft or clearance clashes are the ones that appear when elements are not given the spatial tolerances needed or if a buffer zone is breached. According to her, these interferences might not be caught in automatic clash-detection software since it only considers physical overlaps between two objects. Therefore, “it has become common practice to create objects representing required clearances, to enable clash detection software to catch soft clashes.” Besides, Leite highlights that subcontractors only tend to increase the LOD of their BIM models by manually adding the clearances required for equipment to be accessed. If that knowledge was shared and made visible at earlier stages of the project’s execution, interferences that affect the operational phase will be overseen and considered earlier, without representing a tangible monetary value.

Usually, and as reported by Hanlon and Savino, tacit knowledge resides in the heads of experts, while explicit knowledge is easier to share and communicate within project stakeholders. A plausible way to introduce that knowledge and make it visible in the detection and trade coordination process is with the representation of that information in the form of clearance boxes, installation paths, workspaces, and temporary structures (Leite, 2019, pg.97).

4.2 Methodology

Based on the research questions and their goals, the intended process to develop the proof of concept (PoC) was divided into three phases, introduced, and explained below:



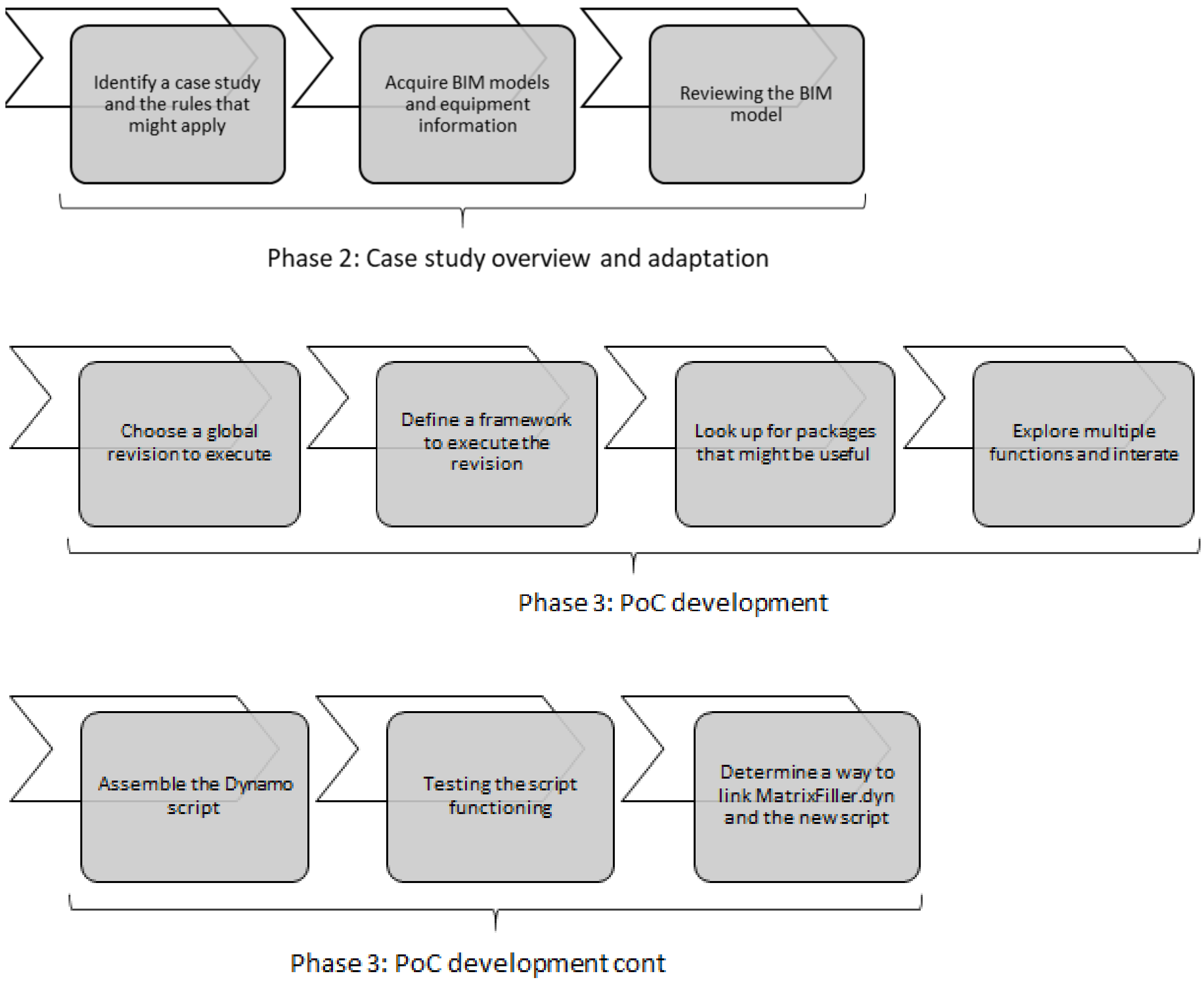


Figure 16 –PoC development methodology

4.2.1 Phase 1: Knowledge

The first phase of the project’s development is related to knowledge gathering and evaluation. An extensive literature review was developed in order to understand the working principles of code compliance tools, their limitations, existing solutions, and current applications that can be further incorporated in the proposal. Afterward, it was essential to understand rule translation, since “the nature of human languages (which includes vagueness and ambiguity) is one of the central drawbacks to transcribe rules and make sure the computer understands them effectively" (Nawari, n.d.). Therefore, understanding alternatives to decode and introduce a lack of subjection to building restrictions are required to implement the desired restrictions further. Later on, it was vital to define the expected coordination workflow with the implementation of the PoC. That way, plausible obstacles or limitations were identified through a structured thought process and before putting together the schema to be later framed and created. Last, a detailed review of the building blocks of Python and Dynamo was developed before putting hands-on creating the scripts.

4.2.2 Phase 2: Case study overview and adaptation

Identifying a case study and the rules that might apply to it was the first step of the second phase. A standard type of space, part of a specialized building type (e.g., laboratory), has attached an opportunity to characterize the restrictions that apply to it and verify the effectiveness of the proposal. With the plausible case studies in mind, the next step was acquiring the BIM models that will serve as a baseline to review and apply the rules. Two models were acquired: a metabolomic lab and an educational building, which will be further described in Section 4.6. Last, both BIM models were reviewed in order to identify potential revisions to make and also, to verify their level of completeness for the intended purpose.

4.2.3 Phase 3: PoC development

Once the BIM models are at hand, and the construction, accessibility, and other restrictions applicable were identified, a universal revision was chosen to be reviewed first. Afterward, a scope of application and architecture to develop the revision, according to the already known restrictions, was determined. Based on the preestablished architecture, the packages and functions needed to connect Dynamo and Revit and to perform the overviewed process effectively were sought and found. With the packages at hand, different attempts were developed to choose the functions that better reflect the intention of the PoC. Later on, the Dynamo script with the entire process was assembled, understanding the sources of information, outputs, and Python functions required to make the PoC a reality. Last and based on the PoC functioning principles, an alternative to connect it with the script developed in Section 4.6.2 was determined.

4.2.4 Assumptions

- All the construction trades provided their own BIM model, with the necessary LOD predefined in their BEP.
- There is no need for a pre-check-in any of the cases that will be further introduced. Everything needed for verification is already contained in the model.
- The rules will have a white-based approach, which means that the user will manually input the information on equipment and other restrictions.

4.3 Expected workflow with the proof of concept and supporting statements of its development

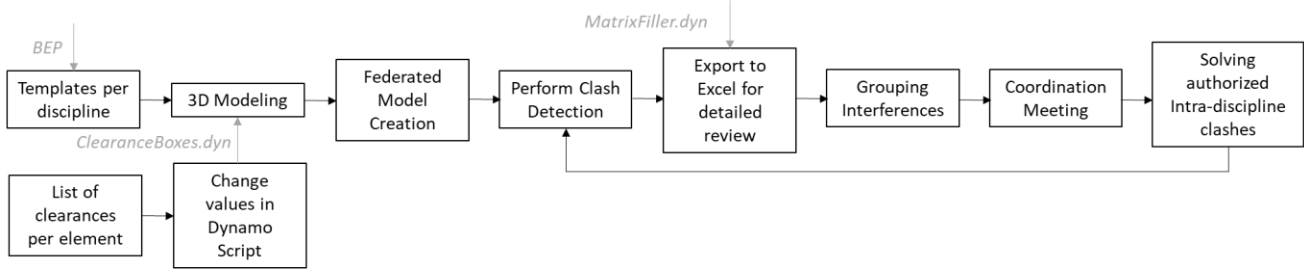


Figure 17 – Expected Coordination Workflow using the proof of concept

Leite (2019) believes that “efficient file sharing allows clash detection and constructability analysis to run smoothly.” In order to avoid common interoperability issues that are attached to the shift from an authoring tool to a support tool, the PoC is developed within the same authoring environment (Revit - Dynamo). Figure 17 introduces the expected workflow of coordination once the proof of concept is run. In the beginning, the project participants determine the naming and color code conventions, families, and the LOD per discipline, in the BEP and make sure all this information is reflected in their templates. Once all disciplines are modeled, the clearances required for the sprinklers, mechanical and electrical equipment, among other restrictions, are introduced in each BIM model using the PoC (ClearanceBoxCreation.dyn). Later on, the federated model, their sets, and tests are created, including the ones related to accessibility for performing maintenance tasks. Afterward, clash detection is performed, and the results are exported to Excel using the MatrixFiller.dyn script. With the information easily accessible and filtered on the Excel file, interferences can be reviewed and grouped during the coordination meetings. That way, coordination meetings, besides being shortened, are executed smoothly, and noise clashes are cleaned out (Leite, 2019). Intra-discipline interferences are solved, the responsible parties change their models according to the meeting agreements, and the BIM Manager performs clash detection all over again. The Excel file, as highlighted in Chapter 3, allows the record of the interferences evolution and the identification of trends and conflictive systems.

4.4 Navisworks Set Up

In order to extract a clash detection report from Navisworks, a particular set up of the files and information exchanges needs to be established first. Almost every clash detection tool requires the use of a federated model, which is a single file that contains references to the 3D models of the different trades that are part of a construction project. Once the federated model is created (using an nwf extension), the program automatically creates a copy of each appended model on its corresponding folder with an nwc extension. After this, the next step is to create searches (Sets) or selections that refer to specific categories within the BIM model and are typically evaluated for clash detection. For example, a group of ceilings and a group of doors can be created to generate a test and review later if one group of elements interferes with the other. Later on, all the tests that are subject to evaluation are created using the Clash Detection tool of Navisworks. Once all tests are created and run, a revision and grouping of the interferences take place. This action frequently implies the creation of rules to disregard certain interferences that are not significant within the defined scope or to reduce the interference results that can be grouped in just one big conflict. It is necessary to recall that the interferences can be exported only to an HTML format for the review during coordination meetings. An overview of the described procedure can be detailed in Figure 18.

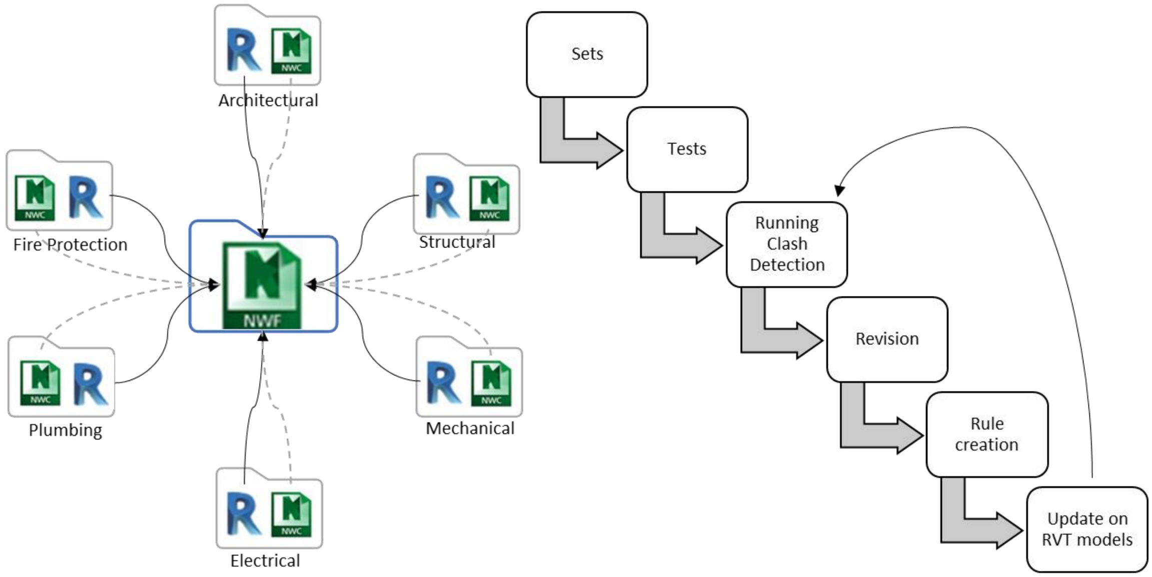


Figure 18 – Federated file set up and clash detection process

4.5 Visual Programming and Dynamo

Visual Programming is an alternative method of automating processes within a three-dimensional environment by using already created functions and procedures, instead of the conventional and elaborate coding approach. Visual programming allows the use of loops, conditional statements, and other predefined routines that various values of parameters that describe objects. Those routines are contained within small blocks or nodes that are connected through wires, allowing the flow of information and the automation of certain procedures. Among the benefits of visual programming is the possibility to customize Revit according to the user needs and without knowledge of the Revit API, the variation of parameters for the desired purpose, and the automation of repetitive tasks that would otherwise require big amounts of time (Mousiadis & Mengana, 2016).

Dynamo is a visual programming tool that can be added as a plug-in into Revit. It allows the generation of new geometries, the modification of existing elements in Revit, the connection of BIM authoring tool with other support tools (Navisworks, Excel, etc.), the import and export of data, among other functions. The nodes in Dynamo are Python scripts that have assigned a specific task that can range from a simple operation to the creation of geometry (Mousiadis & Mengana, 2016). Dynamo nodes include a name, input values that indicate the type of data they receive by hovering over them, output values, and data preview options. The elements mentioned above are highlighted in Figure 19.

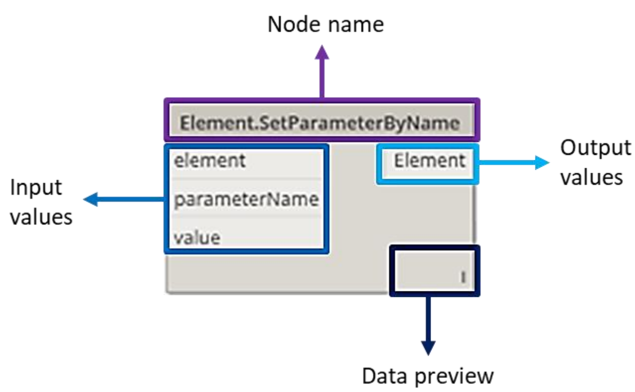


Figure 19 – Node composition

Among the Dynamo building blocks are selections methods, function nodes that include creating data, action data (perform with existing information) and query data (check information to proceed) and packages, which contain selection methods and function nodes developed by Dynamo users. Often, the routines contained within the Dynamo packages cover complementary actions that are needed to automate processes and ease the execution of actions within the Revit environment and its support tools.

4.6 Case study: metabolomics laboratory

Laboratories are spaces that have multiple design, maneuverability, equipment, and many other restrictions to allow the performance of trials and tests in a safe environment. The metabolomic laboratory was chosen as a case study due to its variety of equipment and availability of information in terms of specifications (free zones, minimum clearances, etc.). This project is a retrofit of an existing space that resulted from form the joint effort of three universities in Colombia to put together a research center that serves the health, agriculture, and biotechnology industries. An automated introduction of the restrictions above in the BIM model, is expected to ease the retrofit of the existing space, based on the equipment needs and task demands.

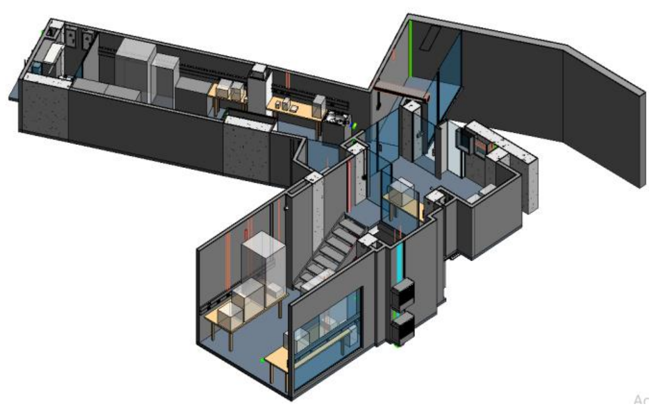


Figure 20 – Laboratory Revit Model

4.6.1 Clearance Box within an object

Overview

This script intends to automatically generate the bounding boxes within certain elements, whose clearances are introduced manually by the user. The metabolomic laboratory model is a perfect case of verification since its varied equipment has many restrictions that need to be considered once the space allocation is performed.

Development

Figure 21 shows the Dynamo script developed to generate the clearance box within an object with a predefined offset.

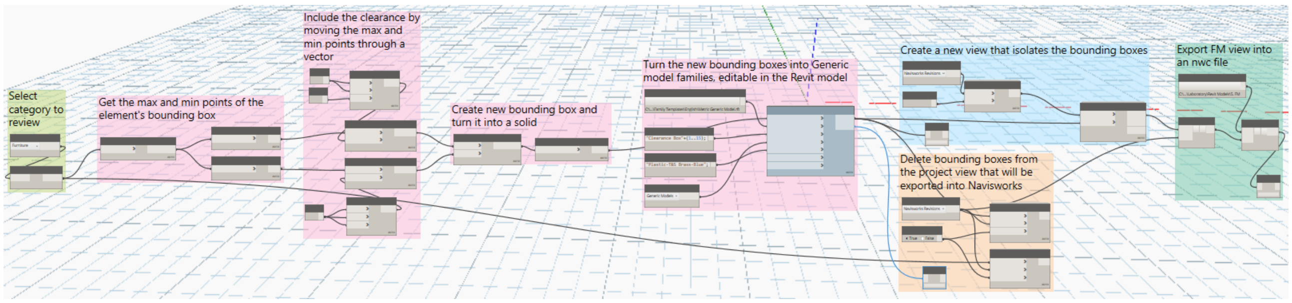


Figure 21 – ClearanceBoxCreation.dyn

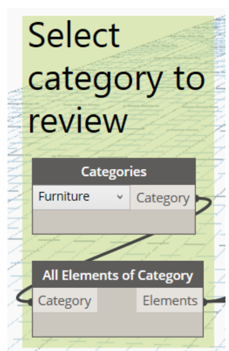


Figure 22 – Select Category to review

The first instruction given to Dynamo is to seek for a specific category within the currently open Revit model to extract all of its elements. Figure 22 shows this instruction.

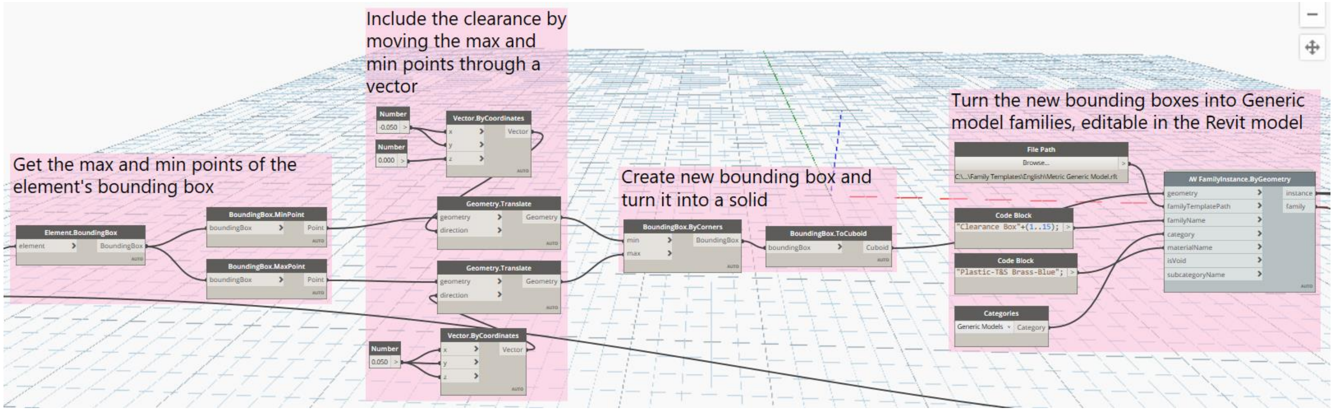


Figure 23 – Retrieving the element's bounding box and creating the object's clearance box

Once the elements of interest are caught, the next step is creating the clearance boxes within them. Figure 23 introduces the workflow of this process, which starts by capturing the maximum and minimum points of the element's bounding box. Afterward, a vector is used to translate those initial points to the end points that include the clearance values in the X, Y, and Z coordinate axes. Later on, the new clearance boxes are translated into solid representations in Dynamo, which are later turned into Generic Model families that are editable in the Revit model.

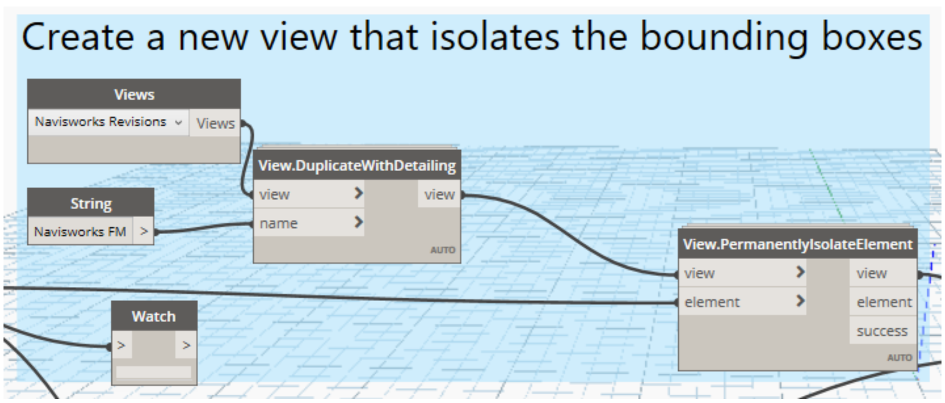


Figure 24 – Creating a view in Revit with the clearance boxes only

In order to make the clearance boxes visible into Navisworks without generating interferences between the host elements and the boxes, a separate view is created. This 3D is a duplicate of the original 3D view in which the recently generated clearance boxes are isolated.

Later on, the clearance boxes are hidden in the original 3D view, which is directly linked to the federated model. See Figure 25.

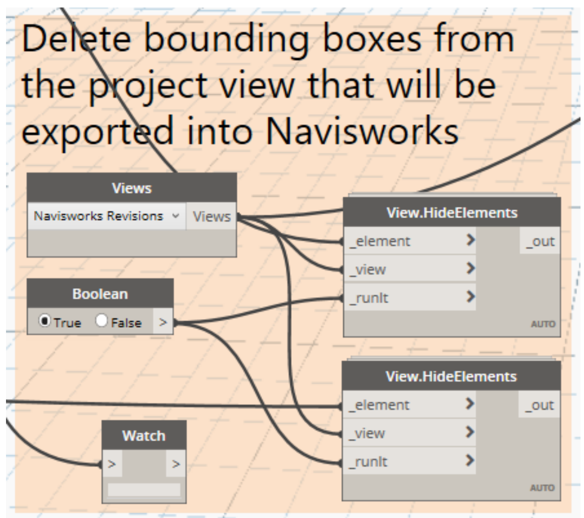


Figure 25 – Removing the bounding boxes from the current view in Navisworks

Last, the 3D duplicate that only retrieves the clearance boxes (FM view) needs to be exported into an nwc file, in order to be later incorporated in the federated model. Consequently, the Export NWC node is used with the directory path in which the user wants to input the export file. This process is detailed in Figure 26.

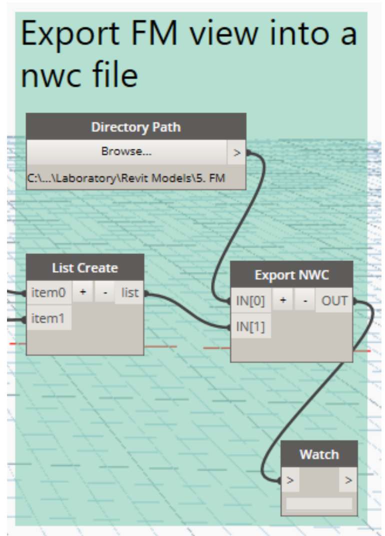


Figure 26 – Export the generated view into an nwc file

The assemble of the Dynamo script that creates the clearances within preestablished objects required the usage of various packages available in Dynamo (archilab, Clockwork, GeniusLoci, and Springs). Packages contain functions in the form of nodes that were created by other users and whose execution was found useful to automate repetitive tasks within the Revit environment. Figure 22 to Figure 26 provide further detail of the steps required to create the clearance boxes and make them visible in the clash detective environment. Firstly, the elements to be reviewed are selected. Later on, the minimum and maximum points that define the bounding boxes of those objects are retrieved. The user introduces the clearance value to create the boxes. A vector is used to move the minimum, and maximum points of the bounding box to a new location, which includes the clearance value in the coordinate axes X, Y, and Z. Once the clearance box is created in Dynamo, it is turned into a solid and later into a family. That way, the solid can be exported into Revit and recognized as an element for detection. In order to introduce the clearance boxes as elements into the Navisworks workspace without disrupting (generating interferences) with the elements that are contained in them, an nwc export of a 3D view that encloses the boxes only, is required. The process of the Navisworks import and the clash detection generation is explained in Section 4.3.

4.6.2 Coordination Matrix execution using Dynamo

In order to materialize the definition of the matrix concept defined in Section 2.8, a Dynamo script was put together to extract the interferences directly from Navisworks and introduce them in an Excel file. This sequence allows the retrieval of the coordination evolution and applying the Color Scale use directly to the Excel sheet. Therefore, the automated gathering of data attempts to ease the recording of information and the visualization of trends in interference resolution. With this approach, the detection of conflictive systems and the traceability of trades that have made significant changes are eased. The principal input of the Dynamo file is the route to the federated model that contains all the interferences found after performing the clash detection revision. The Dynamo file named *MatrizFiller.dyn* can be divided into three significant components, which are shown in Figure 27. The first one uses the Dynaworks package to extract the clash detective report from Navisworks; the second one arranges the retrieved data as lists to later print those in a matrix on a targeted Excel file, which is the third step. Figure 28 to Figure 30 are snips from the Dynamo file, whose creation logic is explained below.

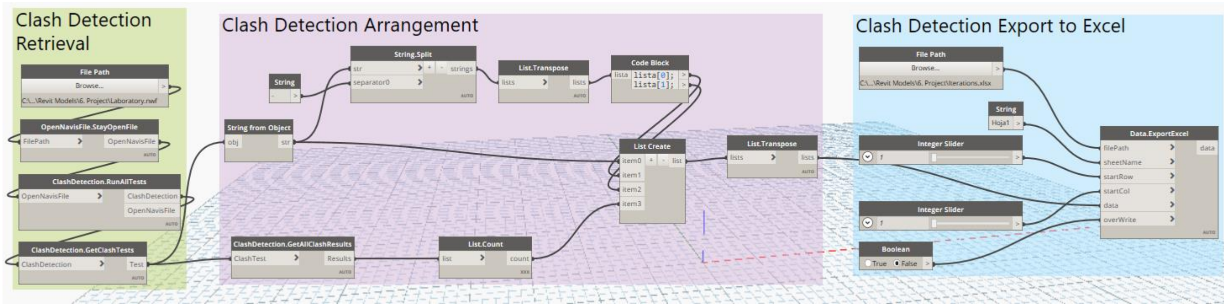


Figure 27 – MatrixFiller.dyn Dynamo Script

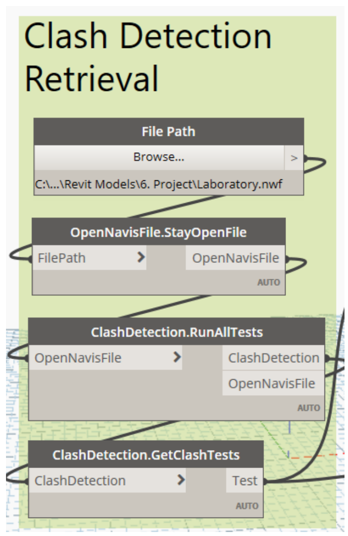


Figure 28 – Clash Detection Retrieval

The first major component of the MatrixFiller.dyn script is the Clash Detection Retrieval. To capture the test results from the federated file, its file path needs to be provided as an input of the OpenNavisFile.StayOpenFile node. Once the file is opened, the clash detection tests are rerun and capture for their export.

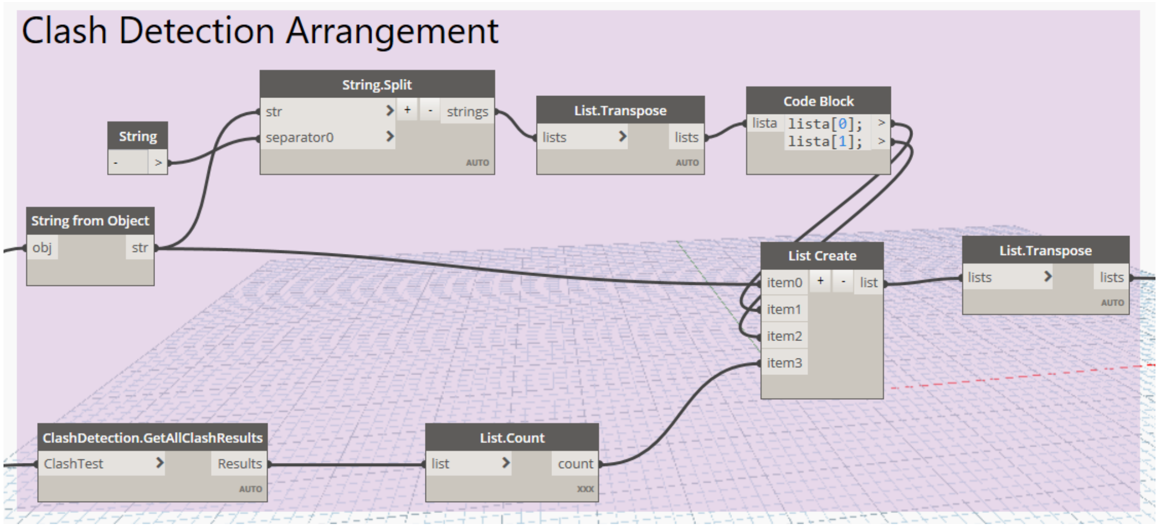


Figure 29 – Clash Detection Arrangement

Figure 29 introduces the functions required to arrange the clash detection tests within the Dynamo environment and before those are exported into Excel. A list of elements is created by introducing the clash values attributable to the test name, trade of the rows, trades of the columns, and the number of interferences (new and active).

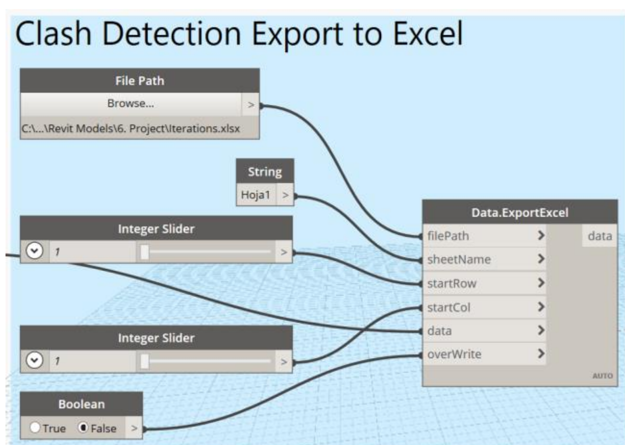
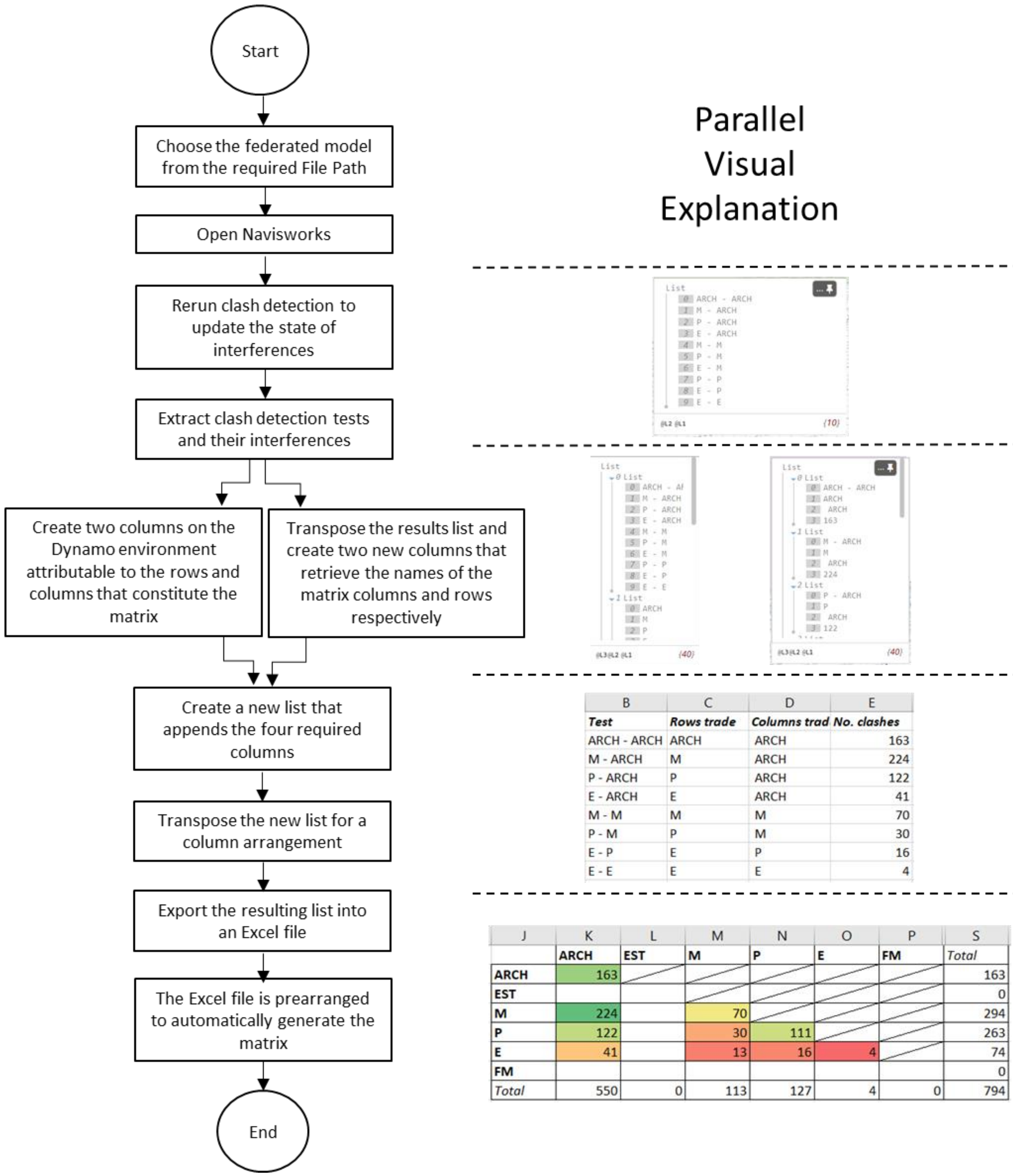


Figure 30 – Clash Detection Export to Excel

The export of clash detective data into Excel using Dynamo was performed with the Dynaworks package and, more specifically, with the Data.ExportExcel node, as shown in Figure 30. All the information was captured as lists, reordered, translated, and put together to ease the workflow in the Excel environment.

Figure 31 introduces the detailed flowchart explaining the process contained in Figure 27, alongside visual support of the steps as they are carried out once the script is run. The clash detection results in Navisworks are provided in a table form, but Dynamo only works with geometry values and lists. Therefore, strings are used to capture each one of the columns of the table as lists and merging them in a unique list array that eases the export from Navisworks into the Excel predefined file. The last has an established table with headers as a reference to paste the upcoming information from Navisworks. A transpose function is used to integrate the headers of the coordination matrix, and the function VLOOKUP () is used to introduce the test results from the match between each row-column combination.

The scope of this research work is intended to develop a Dynamo file that makes clearances required for maintenance tasks visible during the coordination procedure using BIM tools. The inclusion of these restrictions on the same authoring environment helps to avoid potential interoperability issues that lead to information loss when shifting from a software platform into the other. (Leite, 2019)



B	C	D	E
Test	Rows trade	Columns trad	No. clashes
ARCH - ARCH	ARCH	ARCH	163
M - ARCH	M	ARCH	224
P - ARCH	P	ARCH	122
E - ARCH	E	ARCH	41
M - M	M	M	70
P - M	P	M	30
E - P	E	P	16
E - E	E	E	4

J	K	L	M	N	O	P	S
	ARCH	EST	M	P	E	FM	Total
ARCH	163						163
EST							0
M	224		70				294
P	122		30	111			263
E	41		13	16	4		74
FM							0
Total	550	0	113	127	4	0	794

Figure 31 – Logic creation of MatrixFiller.dyn

4.6.3 Limitations

- Coordinate system: the bounding box function returns the element's bounding box considering the XYZ coordinate system as a reference point. Therefore, if the BIM model is not aligned to the XYZ coordinate system, the clearance boxes will not contain the element as desired and will be placed with respect to the origin.
- Axonometric elements: elements that have different alignments respect to the XYZ axes, will not have a well-defined bounding box either.
- The element's location: depending on the host of an object in Revit, the clearance box needs to be created in a specific direction and considering certain constraints.
- Linked models: Dynamo does not perform changes on linked models. Therefore, the script needs to be run for each model independently.

CHAPTER 5. SCALABILITY OF THE PROOF OF CONCEPT

This chapter introduces the feasibility of developing a plugin that covers multiple code compliance restrictions, addresses them on the BIM authoring tool, and makes them visible during the coordination procedure. The assumptions, tool description, possible competitors, differential factors, and outreach strategies are introduced as a part of this chapter.

5.1 Introduction

The construction industry is undergoing an innovation and entrepreneurial atmosphere that is increasing the investment in software solutions that cover AECFM capabilities and look to improve the average time and effort spent during the project's lifecycle. On its Reinventing Construction Report, McKinsey Global Institute (2017) determines that in order to increase construction's productivity, which lags behind other sectors, some interventions are needed to take advantage of the innovation breath that is taking place worldwide. Among the advances in digital technology introduced by the report is the 5D BIM, which entails the introduction of schedules and cost in the 3D representation of the project to improve the decision-making and digital collaboration and mobility. The latter stands for the introduction of apps and, therefore, mobile devices that allow the up to date retrieval and tracking of data, enabling a faster report generation, problem solution, and overall, strengthening the participation of all project stakeholders. These approaches constitute an alternative way to disrupt the traditional interventions that are still taking place in project development.

An article from ENR's November 2019 Issue, entitled Construction Tech's Startup Scramble, also points out that the construction industry is undergoing a period of continuous investments in construction tech, due to a "need of changing the actual landscape and get risk left behind" (Rubenstone, 2019). There are high expectations regarding the construction technology evolution within the next five to ten years. Some of the addressed inventions include the automation of long-lasting processes, the introduction of artificial intelligence algorithms to speed up project resolution, faster ways of accessing documentation, software solutions that connect with physical gadgets, among others. On the same lines, the 3rd Edition of the BIM Handbook (Sacks et al., 2018b), recognizes that the research on BIM alongside the progress in computer power and the incorporation of remote sensing technologies, information exchange technologies, among others, are giving software vendors and entrepreneurs the raw material to come up with new solutions. These alternatives might enable a more secure, faster, and thoughtful construction. The fact is supported by the increase in the number of construction companies funded between 2010 and 2015 (See Figure 32).

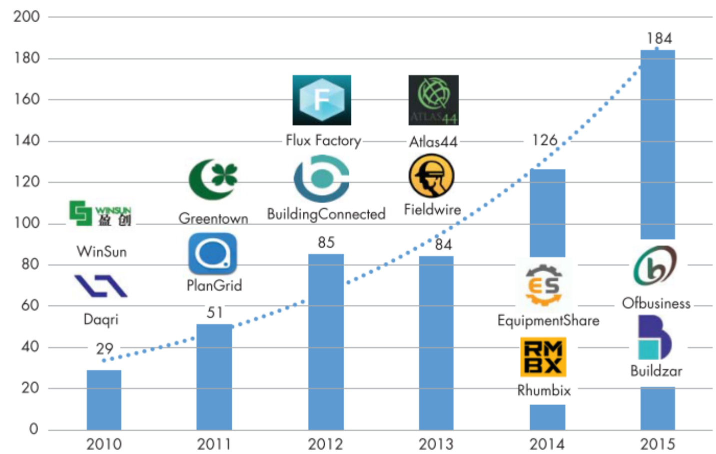


Figure 32 – No. of construction technology start-up companies founded, 2010-2015. (Sacks et al., 2018b)

5.2 A Revit Plug-in

The emergence of new technologies that include software, equipment, and clouds has brought growing opportunities for different industries. Despite the big room to improve the productivity of the construction industry through those solutions, there is still room for the automation of existing BIM authoring tools in order to promote useful and timely compliance of projects within the proposed budget and quality. This is supported by an increase in the development of software plug-ins, which allow the generation of new methods. Those introduce considerations and procedures that are not covered by the authoring tool but require the usage of elements that are incorporated into it. All things considered, a plausible approach to extend the applicability and scalability of the intended proof of concept of this research, is integrating a plug-in solution for Autodesk, Revit that works with the information retrieved in the BIM model and performs a compliance revision that is aligned with the coordination procedure predefined on Chapter 3.

This type of plug-in needs to be implemented using the Revit API, which grants the introduction of functionality to the existing script and allows the modification of data contained within the BIM model. This customization approach added to Revit's interface as an icon that retrieves a function could be potentially extended for user's modification, who might be able to create their own rules, depending on their expertise and lessons learned from past projects. This builds upon the 2018 BIM Handbook affirmation that "Rule checking should not be a capability that requires advanced programming expertise, but it should be easily applied by a wide range of users." (Eastman & Lee, 2018)

5.3 Plug-in Integration Based on Proof of Concept

As mentioned in the paragraph above, the proof of concept might eventually be extrapolated into a plug-in that eases the revision of maintainability, accessibility, and other code restrictions within the same BIM authoring tool and as a part of the coordination procedure. A tool like this will ease the revision of cases during the project design and construction, bringing positive benefits to the O&M stage. A database or rule repository that includes normative data such as the International Building Code (IBC), The Americans with Disabilities Act (ADA), Ergonomic guides, Occupational Safety and Health Administration (OSHA)'s confined spaces, among others, needs to be introduced as an input of the plug-in. Once activated, the plug-in will show up this type of restriction while the user is modeling on Revit and performing coordination reviews. A starting point for the revision could be choosing the codes applicable to a particular state and create its attached rules. Figure 33 example summarizes the construction codes applicable to the state of Georgia.

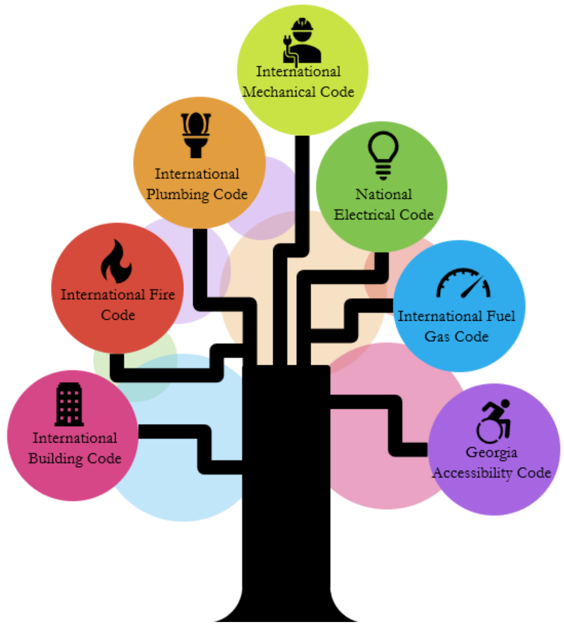


Figure 33 – Summary of Construction Codes in Georgia, USA.

This global framework of rule translation and visualization can provide modelers with a decision-making tool that will further allow them to proceed without reaching out directly to the codes or other construction stakeholders, depending on the type of restriction that is being evaluated. Moreover, specific restrictions (depending on the type of facility) can be isolated and grouped in a rule repository for further revisions. This grouping might consolidate a framework of advanced simulation tools, addressed by the 3rd Edition of the BIM Handbook, as "an automated design review software for different building types" in its 2015 vision. (Sacks et al., 2018)

A more futuristic approach of the tool includes the introduction of machine learning algorithms that are capable of providing rerouting alternatives after the revision of a specific interference or code violation plus their attached implications in terms of cost and space coverage. The simultaneous provision of information in those regards equips the user with alternative scenarios that can be directly compared and leveraged, allowing a better decision-making environment based on the project's desired outcomes. Leite (2019) envisioned that a future approach to design coordination includes working in a collaborative environment in which it is easy to identify the work of other trades in real-time and having a system that can automatically route and size trades and correct interferences. Therefore, an accurate digital transformation and automation in design coordination will be reached. Leite (2019) also highlights the capability of "retrieving expert decisions in an object-oriented and computer interpretable manner and using machine learning techniques for knowledge reuse" (p. 151).

5.4 Competitors

5.4.1 BIM Assure

BIM Assure is a cloud-based rule checking platform that allows own rule creation to check data against project requirements and has predefined checks that are mostly used during the design stage. It is connected directly with Revit, allowing a smooth process for error review and correction on the authoring tool. Its working principle relies on a pre-screen process of matching objects with the categories contained within the rules.

5.4.2 Solibri Model Checker

Solibri uses an Industry Foundation Classes (IFC) project model in order to apply the same set of predefined rules to practically any model open in different BIM authoring tools. It allows the definition of reviews based on the existing material and allows the creation of new reviews. It also includes Building Coordination Format (BCF) to identify failures in rules that are applied directly to the BIM models and made visible within projects.

5.4.3 SmartReview APR

SmartReview APR is a rule checking platform that places information related to the International Building Code and applies rules to check those code provisions directly in Revit building models. Those include the chapters 5-9 and 10, which cover circulation, physical constraints, fire protection, among other restrictions. The rule checking process starts with the review of the Revit model and data gathering and export to a cloud, in which the analysis takes place. Afterward, non-compliant elements are highlighted in Revit so that the user can perform the needed changes. Clouds are a reliable rule source since most of the rules are updated and maintained within it for further use, and new rules are available when needed.

5.4.4 Revizto

Revizto is a cloud-based software that allows collaboration between parties and tracking documents and changes that other parties have made by relying on Navisworks clash groups and reports. It has a user-friendly interface that enables its use for expert and non-expert software users plus allowing the change of platform without irrupting information workflows. Revizto supports different formats, can be integrated into other cloud-based platforms, supports different file formats that include BCF, IFC, Solibri, ReCap and it has plugin solutions for BIM authoring tools (e.g., Revit, Tekla, Vectorworks)

5.4.5 Autodesk Revit Model Review

Autodesk Revit Model Review is a Revit plug-in that facilitates the revision of inconsistencies in terms of geometry, connections, parameter values, visibility, naming conventions, and other representation inconveniences. Users can introduce their checks and extend them to the party intended to revise by using the BCF extension or either rely on preestablished rulesets. When a specific condition is not met, in some instances, the plug-in can select the elements involved for their further revision.

5.5 Added Value of the Plug-in

At first, the plug-in intends to be only an Autodesk Revit supported tool that is capable of sending warnings and code compliance-related notifications, based on the model's LOD and the extent of information available. Those warning messages are gathered and form a repository of machine-translated rules that will consider relationships within the different building systems (i.e., coordination, constructability, and accessibility requirements) as well. This approach is different from the one currently developed by competitors because it does not imply the migration of data from one software solution into another but performs the required reviews in the same environment.

The tool will go beyond the revisions that can be currently done by using Autodesk Model Review. It is expected to incorporate database restrictions that are attached to system requirements, accessibility, and maintainability, the International Building Code (IBC), ergonomics guides, structural, lighting, thermal, and other analyses. Those restrictions will come from a pre-assembled and constantly fed database that keeps updates on regulations. As mentioned earlier, artificial intelligence might be used to develop and compute all the databases above by providing different routing algorithms that solve the identified conflicts.

After adopting this plug-in, users will experience the execution of coordination tasks with less hindered mechanisms, lower time of performance, and the inclusion of code compliance issues without changing from BIM authoring platform. The automated approach will ease the decision-making process by providing alternative routing solutions that cover multiple codes, monetary and schedule constraints, assuring a continuous flow of work and the consideration of multiple restrictions, shortening verification times, and streamlining the execution on site. Therefore, the needs of the facility end-users will be covered in the design decisions for a reasonable price. Besides the automated code compliance and coordination approach, the solution will be complemented with a 24-hour customer service line and live chat through the web page, in order to hear the end-user struggles and feed some of their concerns in the plug-in solution as well.

5.6 Testing the effectiveness of the tool

A plausible way to evaluate the effectiveness of the proposed tool is ensuring that it improves the coordination procedure by reducing the time spent on each iteration and increasing the accuracy of the restrictions sent, allowing timely detection of interferences. Once the tool is comprised of a Plug-in, it is expected to be assessed in parallel with the BIM traditional coordination approach of an ongoing case study. This process will be carried to evaluate the effectiveness of the tool addressing compliance issues through coordination and its benefits. In order to evaluate a possible correlation between the accuracy of the results and the labor hours spent using the proposed tool, hypothesis testing can be developed once the tool is fully available and might strengthen its value proposition. Considering this, the null and alternative hypothesis that need to be tested are:

H0: There is no statistically significant relationship between the compliance accuracy and the time spent on coordination and compliance execution by using the proposed plugin

H1: There is a statistically significant relationship between the compliance accuracy and the time spent on coordination and compliance execution by using the proposed plugin

To further perform the analysis mentioned above, the conceptual framework could include the following variables:

Table 4 – Input variables - Coordination length related

Type	**Variables**	**Descriptions**
Dependent	Coordination length	Time spent in executing the coordination of designs attributable to a project (labor hours)
Explanatory	Coordination approach	Sequential, parallel, or sequential with FM approach (no. interferences solved)
	Accuracy	Total number of restrictions that were addressed by the plugin
	Pre-arrangement of BIM model	Degree of clarity of BIM models required to perform code-compliance tasks (no. corrections required)

Table 5 – Input variables - Price related

Type	Variables	Descriptions
Dependent	Price	The quantification of the price associated with the changes made in the BIM model (US dollars)
Explanatory	Coordination length	Time spent in executing the coordination of designs attributable to a project (labor price)

The variables above are significant due to their alignment with the plug-in purpose. Although it is hard to measure the effectiveness of BIM tools considering that most of their benefits are perceived at the end of construction, it is feasible to rely on the BIM model data and the numbers that result from the execution of specific tasks (most of them object-related).

Further validation of the tool requires its application to a vast pool of case studies, which might bring up specific procedural inconveniences in terms of rule translation, visualization, validation, among others. By including the lessons learned and the customer insights or common issues, the tool will be fine-tuned according to the potential client needs and, therefore, will gain more acknowledgment within the AECFM industry.

5.7 Plausible Barriers

The interest in BIM is increasing, but its adoption is not as easy as it seems. Besides requiring a high initial investment in terms of hardware, software, training, and learning curve, not every stakeholder is willing to shift into a different collaborative environment. According to Unsal & Taylor (2011), the introduction of an innovation in the AECFM industry implies a shift within the organization’s structure first, followed by the systematic changes of the network until it reaches a required stability point. Therefore, altogether how the industry is organized, its pace of adaptation to technological changes, and the way it leverages the challenges collaboratively determine its productivity growth. Like most new software and related methodological solutions, BIM's functioning might be hard to understand and apply until it has been implemented into successive projects. As a result, the trust and collaboration among project participants are strengthened. Trust will eventually allow a greater preparedness for the introduction of same line innovations in the AECFM industry. Some barriers might hinder the development of a plug-in that introduces maintainability and constructability restrictions within its development. This statement is based on the slow innovations assimilation in the construction industry and existing capabilities in terms of software. Those restrictions are depicted in Table 6. There, the BIM model completeness and pre-processing categories are directly related since the completeness is a result of the pre-processing that is carried out, ensuring the achievement of specific objects that met the minimum requirements to perform a planned revision. In terms of computerization, all referred authors agreed on a prior acknowledgment of the rules that can be computerized and a simplification, if possible, of more complex rulesets.

Table 6 – Limitations of developing a rule-based Plug-in

Category	Description	Authors
BIM model completeness	The accuracy, correctness, and consistency of the building model is a necessary prerequisite for the checking process and, therefore, an underlying condition in order to produce resilient results. The results of a checking process are highly dependent on the correctness and availability of the information in the underlying BIM model	Preidel & Borrmann (2018)
	Before a designer can embed the domain-specific knowledge or rules, there is a need for modeling building objects with geometrical constraints, parameters, and construction details	Singh et al. (2015)
Pre-processing	Model objects need to be tailored precisely to the intended meaning of the objects defined in the particular code, standard, regulation, or specification under consideration. Extensive preprocessing by users is required each time a check is performed, being error-prone	Sacks et al. (2018b)
	Need for a pre-checking of screening operation to inform the user of the types of analyses that can be supported with data available in the current base model	Sanguinetti et al. (2012)
Code computerization	Among the different approaches of definition and rule implementation, hard-coding, besides being expensive to translate and hard to run, do not have room for changes. Clearer and specific purpose rules should be contemplated instead	Sacks et al. (2018b)
	It is crucial to realize the limitations of any computerization systems by clearly indicating which part of the codes and standards cannot be computerized	Nawari (2012)
	Existing automated compliance checking tools focus on the relatively more straightforward form of rules. Those lack the capability of performing more sophisticated levels of compliance reasoning and checking, such as checking compliance with contractual requirements	Salama & El-Gohary (2011)
Incorporation of new technologies	There is a reluctance of market users to rely on the tool and new technologies overall	Ghannad et al. (2019)
Representation	Existing rule-checking engines do not provide the level of knowledge representation and reasoning that is needed to process applicable regulations and check conformance of designs and operations of those regulations	Nawari (2012)

CHAPTER 6. CONCLUSIONS, RECOMMENDATIONS AND FURTHER RESEARCH

This chapter provides the revision of results under the light of the research questions and assumptions. It also introduces the challenges found while developing the file and an alternative way to improve the workflow of the process.

6.1 The Proof of Concept

The automated proof of concept tool derived from this study showed that it is feasible to create clearance constraints towards code restricted elements, using visual programming tools. Additionally, those clearance boxes are visible in clash detective software, enhancing their inclusion as the subject of interferences during the coordination procedure. This way, materials and equipment intended for any given space in the building are prevented from physical conflicts or impair the installation and maintenance of individual building systems, as highlighted by Adewale (2016).

With the proposed approach, interoperability issues are avoided, since Dynamo allows the creation, retrieval, and transfer of information within different software without information loss. Moreover, by customizing BIM authoring tools, the design process can be smoother since repetitive tasks are automated. Also, an as-built model can be approached because all the maintainability and accessibility clearances are made visible earlier and encompassed with the trades routing decisions made during coordination meetings.

At present, the verification of strict and long-lasting regulations, such as the Americans with Disabilities Act (ADA) and the International Building Code (IBC), is still pending in already built facilities. This statement brings up to picture an imperative need to include these regulations in the design of retrofits and new construction projects. This way, decision-makers, and designers will be able to include the struggles of physically restricted individuals in their decisions.

6.2 Benefits and Limitations

6.2.1 Further testing the effectiveness of the tool

The proof of concept tool introduced in Chapter 4 is a preliminary overview of the feasibility of creating multiple rules that can be contained on a plug-in. Therefore, the hypothesis testing introduced in Section 5.6. aims to be applied on a real project once a complete framework of rules is put together.

6.2.2 Benefits

By generating the revision of rules within the authoring tool environment, interoperability issues that emerge when changing from one software platform into another are avoided. Using the authoring tool substantially eases the update of systems reallocation within the BIM authoring tool and, therefore, a reduction of interferences reported in the clash detective software.

Soft interferences are not usually caught in visual inspections and might disruptively affect the O&M phase. Those might be addressed in a better way by having all the stakeholders (including the owner or facility manager) involved during the project's conception, design, and construction. The coordination procedure introduced in Section 2.8 ensures that their knowledge and insights wrap up in the decision-making process.

BIM models revolutionized how project components are represented and considered on the schedule, cost estimation, and quality enhancement. Elements can be showed either in a simple or more complex geometric way, depending on the LOD defined in the BEP. Geometric relations such as the empty volume that is required for maintenance of a building part can be created and included using the proof of concept tool.

With the inclusion of clearance boxes in the clash detection tool, we can also oversee elements that need to be installed in relatively confined spaces and also preventing systems from being installed in a manner that hinders the access required to perform operation and maintenance tasks. In practice, those clearance zones and access paths are only modeled by subcontractors in their construction models.

The retrieval of coordination iterations proposed with the MatrixFiller.dyn script on Section 4.6.2 is an alternative way to consolidate an experience repository that can be further used in similar projects to identify trends and include solutions that worked in the past. This approach consolidates a solution to the drawbacks of non-formalized documentation addressed by Leite (2019): loss of knowledge generated during the coordination process, lack of reference material of decisions made in similar projects, and limited access to information.

The focus introduced with the development of the proof of concept can be extrapolated as well to constructability reviews, such as the access paths required to bring in equipment and materials, and clearances around routings to enhance the safety of laborers when developing their job.

6.2.3 Limitations

There are some limitations with this research that will impact not only the development of future tools but also the fine tune of the introduced in CHAPTER 4:

In terms of rule framework definition, it is crucial to have a clear picture of the intended objective and the multiple ways to develop it using visual programming tools. Usually, the most straightforward approach requires fewer operations and, therefore, less RAM consumption to run the methods.

Regarding the document organization and references within the Dynamo scripts, knowing when, where, and what to change in order to run them effectively is crucial to ensure smooth information flow and execution of operations. Therefore, further automation is required to develop an interface that details which elements need to be changed and where.

Concerning the environment to develop the rules, it determines the extent of information that is available for the user to execute its own rules and modify the ones existing or not. The development of this proposal only touched the white-box approach, in which the user is allowed to introduce information and edit parts. The black-box approach might be considered as well, depending on the type of regulation that wants to be automated.

In respect of the accuracy and completeness of the models that are handed over to the BIM Manager for coordination purposes, it is key to somehow include operational restrictions in those to consolidate a detailed design and process modeling, required later on to coordinate at an operational level.

The LOD of the models might influence how interferences are caught or detected by the software and help to minimize the number of false positives when performing clash detection. Therefore, precision in terms of clash detections is directly proportional to the LOD in the BIM model, and a way to identify the completeness and accuracy of those should be used before running the proof of concept script.

The accuracy of the interferences generated by the tool needs to be evaluated to know the extent to which results extracted are false positives or not. Therefore, it is important to figure out if the results generated and extracted by the proof of concept are significant. According to Leite (2019), the typical rule of thumb is that only 20% of what clash-detection software outputs as clashes are relevant.

6.3 Further research

Further research in this study includes a plausible application of machine learning to an ongoing design project in order to provide intelligent routing alternatives to perform coordination tasks. This approach will constitute a system that somehow changes predictability, productivity, and performance of the built environment before its completion. Automating the routing and auto-correct of clashes is one of the future trends for BIM coordination.

In projects with complex MEP systems, objects may fit perfectly in the model but fail to be installed on-site because of constructability or installation issues. This fact suggests that inadequate process consideration is involved when putting together the design model. Accordingly, constructability knowledge should be included as well as part of the revisions that integrate the proof on concept.

The BIM interoperability tools that were recently launched as an extension for Autodesk Revit can be used to perform the pre-screening operations before applying specific rules to the model. Evaluation of how this interoperability tools work can provide an insight into how incorporating pre-checks in the proof of concept.

Construction codes and other regulations tend to evolve. Therefore, and in order to make the rulesets updated and available to ease the performance of code revision, both a human and computational effort is required to create and keep updated repositories of information.

Tuning the tool is key to determine its degree of applicability within certain cases. Therefore, by performing reviews and iterations with projects of different scopes, inductive reasoning can be developed in order to extract patterns, dependencies within rules and hidden assumptions. The latter can be further considered when putting together the restrictions that apply to specific case studies.

A potential application of the introduced software is aligned with some of the recommendations given by the CESBS report to some programs regarding equity measures: “Elaborate on operational safety requirements for construction workers in addition to safety planning and design”(Equity & Building, 2019). This statement strengthens potential applications of the idea, represented on early evaluation of maintainability, repair, and replacement of objects in the workspace.

6.4 Conclusions

Visual programming tools were used to generate geometry and make it visible in both BIM authoring and support tools (Revit and Navisworks). As a consequence of this effort, Facility Management functions are detectable in clash detection software.

Dynamo was the vehicle that allowed the gathering of geometrical information from certain Revit objects to use it further and create the clearance boxes. The use of multiple preestablished nodes helps with the achievement of this goal. All in all, and as a complete approximation of the proof of concept, a Dynamo package that contains essential revisions, applicable to most facilities, can be performed.

The development of the proof of concept tool demonstrated that clearance boxes that represent the space required to access the built environment could be translated into solids in Revit and, therefore, be counted in the clash detection report. By making those visible in the interference count, the project stakeholders are ensuring that the accessibility and maintainability reviews are contemplated early and way before changes become waste at the construction site.

Some clearances derived from the ADA regulation can be made tangible in clash detection tools using the clearance box principle. The geometry approach that is enhanced by Dynamo has a clear potential to generate the accessibility clearances defined by the

ADA, with a more detailed approach in terms of spatial concerns, in comparison with the PoC developed in CHAPTER 4.

By customizing BIM authoring tools, the coordination process can be performed more efficiently with the reduction of attempts required when performing repetitive and redundant tasks. The expected coordination workflow introduced in Section 4.3 demonstrates the ease in the export and visualization of interferences in a matrix form.

The introduction of clearance boxes within the objects that required them is a form to transform tacit knowledge into explicit knowledge (rules). Those insights can be articulated or simulated in order to replicate the constructability checking process in the design phase. Therefore, the introduction of the facility manager’s expertise as a part of the coordination procedure is a good approach to integrate those experiences during the design phase.

The PoC introduced in CHAPTER 4 is an effort towards a code compliance tool that foresees accessibility requirements using BIM coordination and not a BIM-enabled FM approach. As a consequence, it aims to help the development of the as-built model, searchable for consultation when needed by the owner or his representatives.

The PoC that resulted from this research effort demonstrated the ability to cover tasks that involve accessibility to repair, install, replace, or conduct maintenance on components and equipment of the building. As a result, the allocation of systems of a facility under design is eased with its introduction.

Information on a project that is retrieved at its early stages has a strong influence on the facility management phase. Subsequently, the creation of clearance boxes that can be recognized in the clash detective software as accessibility restrictions will have an impact on the project’s execution in the long run.

BIM’s underlying potential to be extended for maintainability studies that address accessibility and preventive maintenance, was acknowledged by Becerik-Gerber et al., (2012). The usage and implementation of the PoC introduced with this research eases the overview of openings that will further allow the addition and removal of equipment parts. Moreover, the tool enhances preventive maintenance with a virtual inspection of the space required to access elements that need to be easily reached for repair and also, intensifies the follow up of components that should be protected from fall-of-roof damage and other potential accidents.

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